AUGUST 2021

M.Sc. in Civil Engineering

ENES TABAK

HASAN KALYONCU UNIVERSITY
GRADUATE SCHOOL OF
NATURAL AND APPLIED SCIENCES

EFFECT OF COVERAGE RATIO TO PULLOUT BEHAVIOUR IN MECHANICALLY STABILIZED EARTH WALLS

M.Sc. THESIS
IN
CIVIL ENGINEERING

BY
ENES TABAK
2021 AUGUST

Effect of Coverage Ratio to Pullout Behaviour In Mechanically Stabilized Earth Walls

M.Sc. Thesis

In

Civil Engineering

Hasan Kalyoncu University

Supervisor

Prof. Dr. Hanifi ÇANAKCI

By

Enes TABAK

AUGUST 2021

INSTITUTE OF GRADUATE STUDIES
M.Sc. ACCEPTANCE AND APPROVAL FROM

The thesis with the title of “**Effect of Coverage Ratio to Pullout Behaviour In Mechanically Stabilized Earth Walls**” which has been prepared and submitted by Enes TABAK, student of Master Programme of Civil Engineering Department, defined successful at the thesis defense on the date of 13/08/2021 and accepted by the jury as a M.Sc thesis.

Position	Title, Name and Surname Department/University	Signature:
Supervisor	Prof. Dr. Hanifi ÇANAKCI Civil Engineering/ Hasan Kalyoncu University	
Jury Member	Dr. Öğr. Üyesi Nurullah AKBULUT Civil Engineering/ Hasan Kalyoncu University	
Jury Member	Dr. Öğr. Üyesi Gökhan ALTAY Civil Engineering/ Osmaniye Korkut Ata Üniversitesi	

This thesis is accepted by the jury members selected by institute management board and approved by institute management board.

Prof. Dr. İbrahim Halil GÜZELBEY
Director

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.

Enes TABAK

ABSTRACT

EFFECT OF COVERAGE RATIO TO PULLOUT BEHAVIOUR IN MECHANICALLY STABILIZED EARTH WALLS

TABAK, Enes

M.Sc. in Civil Engineering

Supervisor: Prof. Dr. Hanifi ÇANAKCI

August 2021, 48 pages

Mechanically stabilized earth (MSE) wall type is one of the most popular retaining wall types of all due to their engineering advantages. The internal stability controls of this wall type, is the main difference between it and other conventional retaining wall types. The internal stability controls contain tension and pullout failure modes to be controlled. Steel strip type of reinforcement is broadly used in the design of MSE walls and pullout failure mode is an important aspect to be checked when it comes to this reinforcement type and coverage ratio is one of the governing factors for it. Center to center horizontal spacing and reinforcement width are main components of the coverage ratio. Corrosion is another aspect to be checked when it comes to steel material type and galvanization is commonly used method to postpone the expected corrosion effect, yet cut edge corrosion is often neglected factor due to their negligible reduction effect to tension strength. Nonetheless, cut edge corrosion affects the pullout behaviour as well, although it is relatively little. In this study, a parametric study is conducted on a baseline case in order to investigate the effect of coverage ratio to pullout behaviour of MSE walls reinforced with steel strip reinforcement type. In this regard, Python programming language is used to construct a calculation procedure for design of baseline case, implication of different center-to-center horizontal spacing values and application of strip width with and without cut edge corrosion. Results of the study indicates that, center-to-center horizontal spacing may play a crucial role in failure when it is chosen in critical state. Results has also shown that cut edge corrosion may cause deficiency in reinforcement amount by the end of design life time and it should be taken into consideration at the design stage.

Keywords: MSE Wall, Steel Strip Reinforcement, Cut Edge Corrosion, Pullout

ÖZET

MEKANİK OLARAK STABİLİZE EDİLMİŞ TOPRAK DUVARLARDA ÖRTME ORANININ SIYRILMA DAVRANIŞINA ETKİSİ

TABAK, Enes

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Hanifi ÇANAKCI

Ağustos 2021, 48 sayfa

Mekanik olarak stabilize edilmiş (MOSE) toprak duvar tipi, mühendislik avantajları nedeniyle en popüler istinat duvarı tiplerinden biridir. Bu duvar tipinin iç stabilite kontrolleri, diğer geleneksel istinat duvarı tiplerinden farklı olarak yapılmaktadır. İç stabilite kontrolleri, kontrol edilecek çekme ve sıyrılma yenilmelerini içerir. Çelik şerit tipi donatı, MSE duvarlarının tasarımında yaygın olarak kullanılmaktadır ve bu donatı türü söz konusu olduğunda, sıyrılma yenilmeleri, kontrol edilmesi gereken önemli bir husustur ve kaplama oranı bu durumu yöneten ana faktörlerden biridir. Merkezden merkeze yatay boşluk ve donatı genişliği, kaplama oranının ana bileşenleridir. Korozyon, çelik malzeme tipi söz konusu olduğunda kontrol edilmesi gereken bir diğer husustur ve beklenen korozyon etkisini ertelemek için galvanizleme yaygın olarak kullanılan bir yöntemdir, ancak kenar korozyonu, çekme mukavemeti için çok az seviyedeki etkisinden dolayı genellikle ihmal edilen bir faktördür. Bununla birlikte, kenar korozyonu, nispeten az olmasına rağmen, sıyrılma davranışını da etkiler. Bu çalışmada, çelik şerit donatı tipi ile güçlendirilmiş MOSE duvarların kaplama oranının, sıyrılma davranışına etkisini araştırmak için bir referans tasarım üzerinde parametrik bir çalışma yapılmıştır. Bu bağlamda, Python programlama dili, referans duvarın tasarımı, farklı merkezden merkeze yatay aralık değerlerinin uygulanması ile kenar korozyonlu ve korozyonsuz şerit genişliğinin uygulanması için bir hesaplama prosedürü oluşturmak için kullanılmıştır. Çalışmanın sonuçları, merkezden merkeze yatay mesafenin kritik durumda seçilmesi halinde, yenilmede çok önemli bir rol oynayabileceğini göstermektedir. Sonuçlar ayrıca, kenar korozyonunun tasarım ömrünün sonunda donatı yetersizliğine neden olabileceğini ve tasarım aşamasında dikkate alınması gerektiğini göstermiştir.

Anahtar Kelimeler: Toprakarme Duvar, Çelik Şerit Donatı, Kenar Korozyonu, Sıyrılma

ACKNOWLEDGEMENTS

I would like to sincerely thank to my supervisor, Prof. Dr. Hanifi ÇANAKCI, for his mentorship during the preparation process of this study. Nonetheless, I would like to thank warmly to my wife, for her patience and unconditional support.

TABLE OF CONTENTS

ABSTRACT II

ÖZET III

ACKNOWLEDGEMENTS IV

TABLE OF CONTENTS V

LIST OF FIGURES VII

LIST OF TABLES VIII

LIST OF CODES IX

CHAPTER 1 1

INTRODUCTION 1

CHAPTER 2 5

MATERIALS AND METHODS 5

- 2.1. GEOMETRY OF THE MSE WALL 5
- 2.2. REINFORCEMENT INFORMATION 6
- 2.3. SOIL PROPERTIES 8
- 2.4. UNFACTORED LOADS AND DESIGN FACTORS 9
- 2.5. EXTERNAL STABILITY CONTROL 12
  - 2.5.1. Sliding control 12
  - 2.5.2. Turnover Control 14
  - 2.5.3. Bearing Capacity Control 17
- 2.6. INTERNAL STABILITY CONTROLS 20
  - 2.6.1. Tensile Failure Control 23
  - 2.6.2. Pullout Failure Control 24
- 2.7. PARAMETRIC STUDY COMPONENTS 28
  - 2.7.1. Center-to-Center Horizontal Spacing 28
  - 2.7.2. The Cut Edge Corrosion Effect 30

CHAPTER 3 32

RESULTS AND DISCUSSIONS 32

- 3.1. RESULTS OF EXTERNAL STABILITY CONTROLS 32
  - 3.1.1. Sliding Control 32
  - 3.1.2. Eccentricity Limit Check 32
  - 3.1.3. Bearing Capacity Check 33
- 3.2. RESULTS OF INTERNAL STABILITY CONTROLS 34
  - 3.2.1. Tension Failure Check 34
  - 3.2.2. Pullout Failure Check 35

3.3. RESULTS OF PARAMETRIC INVESTIGATION 36
3.3.1. Pullout after Cut Edge Corrosion........ 39
3.4. DISCUSSIONS 42
CHAPTER 4 44
CONCLUSIONS 44
REFERENCES........ 46

LIST OF FIGURES

Page

Figure 1.1 MSE wall example (Wall System, 2021)…………………………...... 1

Figure 1.2 MSE wall with sloping backfill…………………………………..... 2

Figure 1.3 Steel strip reinforcement (Reinforced Earth, 2019)……………...... 3

Figure 2.1 MSE Wall and potential failure surface………………………..... 6

Figure 2.2 Potential failure surface and graphs to calculate required equation... 20

Figure 3.1 Sh tolerations of different amounts of strips within the wall width... 37

Figure 3.2 Rc – Sh Relation………………………………………………… 37

Figure 3.1 L_{pcr} - S_h relation at design stage…………………………………….. 38

Figure 3.2 Percentage change in L_{pcr} due to cut edge corrosion……………….. 40

Figure 3.3 L_{pcr} change over design life with regard to critical S_h values………. 40

Figure 3.4 P_{res} - L_e relation…………………………………………………... 41

Figure 3.5 Change in required amount of strips as a result of P_{res} decrease……. 42

LIST OF TABLES

Page

Table 2.1 Electrochemical properties of the backfill soil………………………. 8

Table 2.2 Unfactored Vertical Forces and Moments…………………………… 9

Table 2.3 Unfactored Horizontal Force and Moment…………………………... 10

Table 2.4 Applicable Load Factors……………………………………………... 10

Table 2.5 Applicable Resistance Factors…………………………….……….. 10

Table 2.5 Computation Steps of Contributory Area, Sv……………….....…….. 21

Table 3.1 Evaluation of sliding resistance…………………………………….. 32

Table 3.2 Evaluation of eccentricity…………………………………………….. 33

Table 3.3 Evaluation of bearing capacity……………………………………….. 33

Table 3.4 Corrosion calculations for tension failure mode……………………… 34

LIST OF CODES

Page

Code 2.1 Importing stage of relevant Python modules…………………………. 5

Code 2.2 Geometrical information……………………………………………... 6

Code 2.3 Reinforcement Placement…………………………………………….. 7

Code 2.4 Performance criteria and steel strip element info…………………….. 7

Code 2.5 Soil Properties………………………………………………………. 8

Code 2.6 Un-factored loads and load factors……………………………………. 10

Code 2.7 Sliding stability check…………………………………………………. 13

Code 2.8 Turnover Stability Check……………………………………………... 15

Code 2.9 Bearing capacity check………………………………………………... 17

Code 2.10 Array construction for internal stability……………………………... 20

Code 2.11 Initial calculations for internal stability……………………………… 21

Code 2.12 Input for corrosion effect…………………………………………….. 23

Code 2.13 Tension failure check………………………………………………… 24

Code 2.14 Array construction for pullout check………………………………… 25

Code 2.15 Pullout criteria length calculation……………………………………. 26

Code 2.16 Pullout resistance per unit width of reinforcement…………………... 27

Code 2.17 Application of different Sh values and writing results to an excel file. 28

Code 2.18 Application of cut edge corrosion and writing results to an excel file. 30

CHAPTER 1

INTRODUCTION

The mechanically stabilized earth (MSE) walls are one of the most preferred geotechnical retaining structures due to flexibility in design, convenient and cost-effective construction, drainage through wall facing, lower production costs, durability and long lifespan, and environmental compatibility (Elias et al., 2001). These sides of MSE walls, have led them to be a popular choice in many civil infrastructures. This retaining wall type is simply made by reinforcing the earth with relevant construction material types and covering the façade with facing panels. Some overall views for MSE wall with horizontal crest and sloping backfill are shown in Figure 1.1 and Figure 1.2.

Figure 1.1 MSE wall example (Wall System, 2021)

MSE walls are well investigated on their seismic, external stability and internal stability aspects. There are plenty of studies on seismic performance of MSE walls. The pullout failure being governing factor under incitation, MSE walls tolerating larger deformations and thus handling better with seismic activity, different reinforcement materials showing variety of deformation tolerance, different backfill material types showing different performances under seismic activities, are some of the significant conclusions of those studies (Walthall et al., 2013; Wartman et al., 2006; Siddharthan et al., 2004a,b; Hartman et al., 2013).

Figure 1.2 MSE wall with sloping backfill

MSE walls act as any other retaining wall when it comes to external stability checks. Sliding, turnover and bearing capacity of foundation are the main governing failure modes to be checked in MSE walls as it is for conventional retaining walls. Chalermyanont et al. investigated reliability-based design for external stability (Chalermyanont and Benson, 2005). Kim and Salgado studied load and resistant design factors in same regard (Kim and Salgado, 2012). Probabilistic and numerical analysis procedures are also applied to MSE walls in many researches (Zevgolis and Bourdeau, 2008a; Hatami and Witthoeft, 2008; Zevgolisand Bourdeau, 2008b).

Kim and Salgado, focused on development of load and resistance design factor (LRFD) and its equations in order to maintain a better view to internal stability check of MSE walls those are reinforced with steel strips (Kim and Salgado, 2012). Allen et al. Developed simplified method in the design of MSE walls and their study enabled a simpler procedure of design by taken LRFD into consideration (Allen et al., 2001). Researchers have studied many different aspects of internal stability of MSE walls, such as assessment based on life cycle assessment (Huand Luo, 2018), effect of corrosion aggressiveness (Thornley and Siddharthan, 2010), usage of cohesive backfills (Wang and Wang, 1992), effect of differential settlements (Sadat et al., 2018), probabilistic-base analysis (Vahab and Helda, 2018; Bathurst et al., 2020; Chalermyanont and Benson, 2004), analytical and numerical analysis (Drusa et al., 2016; Srivastava and Chauhan, 2020; Liu, 2013) etc.

The pullout failure mode is one of the governing factors when it comes to internal stability check. Current literature contains many works regarding different aspects of this failure mode. Weldu et al. prepared a detailed technical report regarding the pullout performance of MSE wall with steel strips and uniform aggregate backfill. Test materials and apparatus, test procedure and date acquisition and the analysis of data which is received by test are presented in their study. (Weldu et al., 2015). Kim et al, have shown in their study that the maximum pullout force is effecting the uppermost reinforcement and particle size distribution has an important effect on the pullout behaviour (Kim et al., 2018). Tajabadipour et al. conducted 50 laboratory large scale under the application of differing normal stresses. They have used a new generation reinforcement type which is scrap tire. They have validated their laboratory results with theoretical analysis and also compared it to strip elements like steel and geosynthetics strips. They came to a conclusion that scrap tire strips performs much better than the conventional ones (Tajabadipour et al., 2019).

Figure 1.3 Steel strip reinforcement (Reinforced Earth, 2019)

Effect of corrosion in MSE walls is another factor to be investigated carefully in order to maintain internal stability in long term. Thapalia et al. assessed the corrosion potential within MSE walls which have coarse backfill material. It is demonstrated that a more accurate electro chemical assessment is possible in case of crushing the coarse particles (Thapalia et al., 2011). Parsons et al. compared current specification suggestions on soil resistivity with the field results and found measured the accuracy of specifications (Parsons et al., 2020). In another study, Parsons et al. investigated the effect of fine migration in backfill to corrosion potential variation with in MSE walls (Parsons et al., 2019). Bourgeois et al. applied various corrosion scenarios in order to investigate the long-term deformations of MSE walls and the results of study used for discussing the heterogeneity influence of corrosion process (Bourgeois et al., 2013). With regard to corrosion factor, steel strip type is the most vulnerable one inherently. Bligh et al. presented in their study, that approximately 57 percentage of the MSE Walls in United States are built with steel strips (Bligh et al., 2010), which indicates the fact that the steel strip type of reinforcement element is frequently preferred. This reinforcement type is shown in the Figure 1.3. Pullout failure mode is an important component of internal stability check and strip element type is the most convenient one to be investigated from different aspects in this regard, since reinforcement types with full coverage (i.e. geogrid) are usually applied with full coverage. Therefore, reinforcement coverage ratio is a governing component of pullout failure check process (AASHTO, 2010). Although the reinforcement coverage ratio has been a significant concern for many guidelines and specifications (Castellanos, 2010; Christopher et al., 1997; Berg et al., 2009a,b), the effect of it to pullout failure mode with regard to cut edge corrosion is not well studied in the literature.

The objective of this study is to investigate the effect of reinforcement coverage ratio to pullout behavior of MSE wall before and after cut edge corrosion state. In order to maintain this, a baseline case is designed with different amounts of reinforcements in each reinforcement level and a parametric study has been conducted in order to observe the effect of coverage ratio to the mentioned phenomena. Changed parameters are two components of coverage ratio which are reinforcement strip width and center-to-center horizontal spacing between reinforcement elements. Corrosion effect is calculated for the beginning of service life time and the end of it with regard to electrochemical properties those are suggested by The American Association of State Highway and Transportation Officials (AASHTO, 2010). Results of the study indicated that the maximum center-to-center horizontal spacing values which gives the lowest coverage ratio values are the most critical ones and they can cause pullout failure in some reinforcement levels at the end of corrosion process. Results also showed that the lower coverage ratios are resulting with lower pullout resistance which was in the line with relevant design specification.

CHAPTER 2

MATERIALS AND METHODS

Herein through chapter, relevant calculation step based on The American Association of State Highway and Transportation Officials (AASHTO, 2010) is shared primarily, the python code written in this regard is added afterwards, in order to present calculation process of the study within an understandable flow.

Used python modules and a library are presented in the Code (2.1), which is the preamble of the codes within the study. The math module is used for having access to mathematical functions. The numpy library is used for arrays and matrices. The tabulate module is used for obtaining table outputs of desired results. The xlsxwriter module is used to write numerical results into an excel file in order to use for visualization which are shared later in results.

```
import math
import numpy as np
import tabulate as tb
import xlsxwriter as xl
```

Code 2.1 Importing stage of relevant Python modules

2.1. Geometry of the MSE Wall

The codes shown in Code 2.2, are written in order to include the geometrical information given in the Fig.2.1. Overall height of the wall (H) is chosen as 5 m for having a middle size wall and wall batter is chosen as 8◦ for wall to be in the class of vertical or almost vertical wall type as AASHTO (AASHTO, 2010) suggests. The minimum reinforcement length is suggested to be 0.7H in AASHTO (AASHTO, 2010), therefore maximum of the chosen value or 0.7H is programmed to be chosen in order to maintain consistency in this regard, as it is shown in the 7th row of Code 2.2. Effective height of the wall (h) is the height which extends to the top of potential failure surface. There is no slope on the toe of the wall as it is horizontal. Some other geometrical information regarding the base line case is shown in the Code presented by Code 2.2

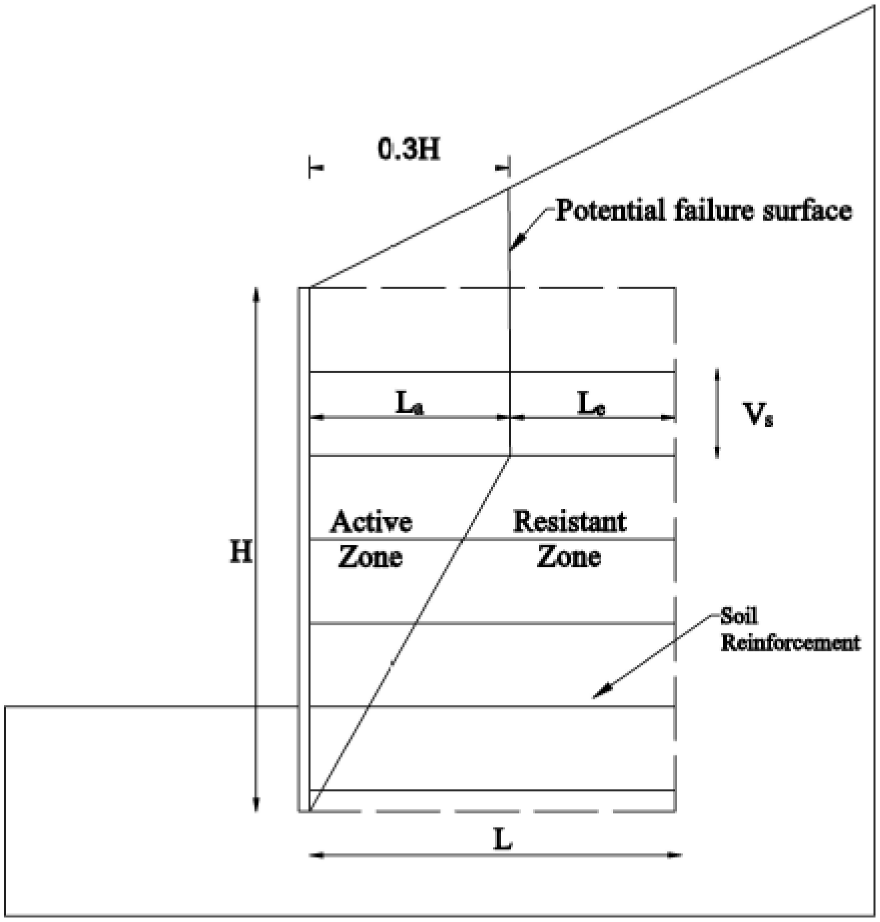

Figure 2.1 MSE Wall and potential failure surface

```
H = 5 # m
d_emb = max(0.6, (H*0.2)) # embedded height of the wall
H_exp = H - d_emb # exposed height of wall
batter = 8 # degree
beta = 18 # degree - crest slope
toe_slope = 0
len_reinf_min = max((H*0.7), 2.5) # static loading with earth surcharge
h = round(H + (len_reinf_min * math.tan(math.radians(beta))),2)
```

Code 2.2 Geometrical information

2.2. Reinforcement Information

This part of design is also based on the decision of designer, apart from specifications. No seismic activity was concerned during design of base line case. Ultimate tensile strength of reinforcement element (T_{ult}) should be chosen in way that it meets the received lateral earth load. Center-to-center horizontal spacing (S_h) is an important parameter for this study as it has been incrementally increased by the multiples. Gross width of the reinforcement strip element (b) is another parameter which is under investigation of this study for before and after corrosion effect. The coverage ratio (R_c) is obtained by the division of b by S_h and it is the main subject of interest for this work. The contributory area (R_v) is decided to be 0.80 m for having variation of strip amount for each reinforcement layer. Note that, it has resulted with almost uniform reinforcement amounts for each level when the value was tried to be 0.40, but it was not fitting the purpose of this work. The facing panel width (w_p) presents the studied area which is bordered within. Rest of the Code is for obtaining a tabular form which presents the mentioned information. This and other reinforcement information are shown in the Code 2.3.

```
reinforcement_type = 'strip'
Tult = 355 # MPa - ultimate tension resistance of the reinforcement - s355 type
Sh = 0.05 # m - center-to-center space between strips
b = 0.05 # m - gross width of one strip
Rc = b / Sh # coverage ratio of reinforcement
R_v = 0.8 # equal vertical spacing between reinforcements
wp = 1.5 # panel width ( it will be used to obtain value of tributary area)
print(50*"-","\nStep 1:\n")
step_1_geometry = (['Exposed Height - H_exp (m)', H_exp],['Full Height - H
(m)', H],
['Effective Height (Crest included) - h (m)', h],
['Slope of Crest (degree)', beta],['Wall Batter (degree)', batter])
step_1_rnf = (['Reinforcement', 'Metal Strip (inextensible)'],
['Ultimate Tensile Strength (MPa)', Tult],['Length (m)', len_reinf_min],['Center-
to-Center Space (m)', Sh],
['Gross Width (m)', b],['Initial Rc Value',Rc],['Vertical Spacing (m)',R_v])
t_s1_geo = tb.tabulate(step_1_geometry, tablefmt="fancy_grid")
t_s1_rnf = tb.tabulate(step_1_rnf, tablefmt='fancy_grid')
print("Geometry Info:",t_s1_geo, "\nReinforcement Info:",t_s1_rnf,sep="\n")
```

Code 2.3 Reinforcement Placement

No seismic activity was concerned during design of base line case. Design life time is chosen to be 75 years, as it is commonly chosen in daily design processes of MSE walls. In addition to these, strip width and thickness with zinc coating information is also presented in Code 2.4.

```
design_life = 75 # years
strip_thickness = 4 # mm
strip_width = 50 # mm
zinc_t1 = 0.086 # mm - on up and down sides of strip
# No zinc coating is assumed to be on the cut edges of strips
```

Code 2.4 Performance criteria and steel strip element info

2.3. Soil Properties

The backfill soil properties are chosen in the conservative way that AASHTO (AASHTO, 2010) suggests. The absence of field testing and requirement of safe design for non-investigated properties of the structure are the reasons that have lead the study to be conducted with the values those are presented in Code 2.5. Tabulating codes for mentioned information is also shown in Code 2.5. Backfill electrochemical properties are assumed to be meeting the optimum requirements as it is shown in Table 2.1.

Table 2.1 Electrochemical properties of the backfill soil (AASHTO, 2010)

Parameter	**Value**
Backfill type	nonaggressive
pH	between 5-10
Resistivity	≥ 3000 ohm-cm
Chlorides	≤ 100 ppm
Sulfates	≤ 200 ppm
Organic Content	≤ 1 percent
Lose of carbon steel per year	0,012 mm
Lose of zinc coating for first 2 years	0.015 mm
Lose of zinc coating for subsequent years	0.004 mm

```
print(50*"-","\nStep 2:\n")
#BHA: Unit weight
#phi: Friction angle
#coh: Cohesion
#back: Retained soil
BHA_back = 18 # kN/m3
phi_back = 34 # degree
coh_back = 0 # kN/m2
#wall: Backfill soil
BHA_wall = 18 # kN/m3 - BHA_wall is preferred to be equal or greater than BHA_back
phi_wall = 34 # maximum value in absence of testing
coh_wall = 0 # kN/m2
#fnd: Foundation soil
BHA_fnd = 18 # kN/m3
phi_fnd = 37 # degree
coh_fnd = 5 # kN/m2
#------------------------
step_2 = (['Section','Unit Weight (kN/m3)','Friction Angle (degree)','Cohesion (kPa)'],
['Retained Soil', BHA_back, phi_back, coh_back],
['Back Fill Soil', BHA_wall, phi_wall, coh_wall],
['Foundation Soil', BHA_fnd, phi_fnd, coh_fnd])
```

```
t_s2 = tb.tabulate(step_2, headers='firstrow', tablefmt='fancy_grid')
print(t_s2)
```

Code 2.5 Soil Properties

2.4. Unfactored Loads and Design Factors

Active earth pressure (K_{ab}) coefficient is calculated as follows:

$$K_{ab} = \frac{sin^2(\theta+\phi'_r)}{\Gamma sin^2\theta \sin(\theta-\delta)} \tag{2.1}$$

$$\Gamma = \left(1 + \sqrt{\frac{sin(\phi'_r+\delta)sin(\phi'_r-\beta)}{sin(\theta-\delta)sin(\theta+\beta)}}\right)^2 \tag{2.2}$$

δ = friction angle between fill and wall taken as specified
β = angle of sloping back to horizontal axis
θ = back face angle of wall to horizontal axis
ϕ'_r = effective internal friction angle of retained backfill

For the baseline case herein, K_{ab} is calculated to be 0.326. Other information regarding un-factored loads for vertical and horizontal implication, applicable load factors, resistance factors are shown in Table 2.2, Table 2.3, Table 2.4 and Table 2.5 respectively. The relevant Code is presented in Code 2.6, at the end of the section.

Table 2.2 Unfactored Vertical Forces and Moments

Vertical Force	**LRFD Load Type**	**Value (kN/m)**	**Moment Arm (m)**	**Moment (kN.m/m)**
V1	EV	315	1.75	551.25
V2	EV	35.91	2.33	83.79
F_{tv}	EH	34.13	3.50	119.45

The vertical earth surcharge (EV load type) has two components which are force from wall weight and sloping backfill, V1 and V2, respectively. The vertical load resulted by horizontal earth thrust (EH load type) is designated with Ftv. These values are calculated as follows:

$$V_1 = \gamma_b HL \tag{2.3}$$

$$V_2 = 0.5L(h-H)\gamma_r \tag{2.4}$$

$$F_{tv} = 0.5\gamma_b h^2 K_{ab} sin\beta \tag{2.5}$$

Table 2.3 Unfactored Horizontal Force and Moment

Horizontal Force	**LRFD Load Type**	**Value (kN/m)**	**Moment Arm (m)**	**Moment (kN.m/m)**
F_{th}	EH	105.04	2.05	214.973

The horizontal load resulted by horizontal earth thrust (EH load type) is designated with F_{th} and calculated as follows:

$$F_{th} = 0.5\gamma_b h^2 K_{ab} cos\beta \tag{2.6}$$

Table 2.4 Applicable Load Factors

Load Combinations	**EV (vertical)**	**EH (horizontal)**
Strength I (max)	1.35	1.5
Strength I (min)	1	0.9
Service I	1	1

Table 2.5 Applicable Resistance Factors

Item	**Resistance Factor**
Sliding on Foundation, ϕ_{sl}	1
Bearing Resistance, ϕ_{br}	0.65
Tensile Resistance, ϕ_{ts}	0.75
Pullout Resistance, ϕ_{pr}	0.9

```
print("Step 3:",
"\033[1mUnfactoed Loads and Load Factors\n\033[0m")
#cof_asst = "Gamma" which is presented within text by the Eq.(2.2)
cof_asst = (1 +
math.sqrt((math.sin(math.radians(phi_back+beta))*math.sin(math.radians(phi_ba
ck-beta)))
                      /
                      (math.sin(math.radians(90-
beta))*math.sin(math.radians(90+beta)))))**2
#Kab = Ka
Kab = round((math.sin(math.radians(90+phi_back))**2)
                                                                  /

           (cof_asst*(math.sin(math.radians(90))**2)*math.sin(math.radians(90-
beta))), 5)
print("Coefficient of Active Earth Pressure (Kab):",Kab)
# Calculate nominal retained soil force resultant per unit width, Ft
Ft = round(0.5 * Kab * BHA_back * (h**2),3)
FTV = 'F{} = (1/2)(\u03B3{})(h\u00b2)(K{})(sin\u03B2)'.format(tv, b, a)
FTH = 'F{} = (1/2)(\u03B3{})(h\u00b2)(K{})(cos\u03B2)'.format(th, b, a)
V1 = H * len_reinf_min * BHA_wall
V2 = ((h-H) * (len_reinf_min/2)) * BHA_back
L = len_reinf_min # L is the width of wall
```

```
# Moment calculations:
mo_arm1_v = L/2 # moment arm for V1
mo1_v = V1 * mo_arm1_v # moment value for V1
mo_arm2_v = (2*L)/3 # moment arm for V2
mo2_v = V2 * mo_arm2_v # moment value for V2
Ft_v = Ft * math.sin(math.radians(beta)) # vertical component of Ft
mo3_v = Ft_v * L # moment value of Ft (moment arm is equal to L)
Ft_h = Ft * math.cos(math.radians(beta)) # horizontal component of Ft
mo1_h = Ft_h*(h/3) # moment arm for horizontal sompontent of Ft
#Tabulating:
step_3_v =(['Vertical Force','LRFD Load Type', 'Value (kN/m)','Moment Arm
(m)','Moment (kN.m/m)'],
['V1 = (\u03B3{})(H)(L)'.format(get_sub('b')), 'EV', V1, mo_arm1_v, mo1_v],
['V2 = (1/2)(L)(h-H)(\u03B3{})'.format(get_sub('r')), 'EV', V2, mo_arm2_v,
mo2_v],
[FTV,'EH', Ft_v, len_reinf_min, mo3_v])
step_3_h = (['Vertical Force','LRFD Load Type', 'Value (kN/m)','Moment Arm
(m)','Moment (kN.m/m)'],
[FTH,'EH', Ft_h, (h/3), mo1_h])
t_s3_v = tb.tabulate(step_3_v, headers='firstrow', tablefmt='fancy_grid',
numalign="center", stralign="center")
t_s3_h = tb.tabulate(step_3_h, headers='firstrow', tablefmt='fancy_grid',
numalign="center", stralign="center")
print("\nUnfactored Vertical Forces and Moments:",t_s3_v,"\nUnfactored
Horizontal Forces and Moments:",t_s3_h, sep="\n")

# Load Combinations: Strength I, Service I
# Load Factors: Table 4-2 FHWA , Table 3.4.1.-2 AASHTO
gama_EHmin = 0.9
gama_EHmax = 1.5
gama_EVmin = 1
gama_EVmax = 1.35
gama_Srmax = 1.0
gama_Srmin = 1.0

# Tabulating:
step_3_load_factors = (['Load Combinations','EV','EH'],
['Strength I (max)', gama_EVmax, gama_EHmax],
['Strength I (min)', gama_EVmin, gama_EHmin],
['Service I', gama_Srmax, gama_Srmin])
t_s3_f = tb.tabulate(step_3_load_factors, headers='firstrow',
tablefmt='fancy_grid', numalign="center",stralign="center")

# Resistance factors are from AASHTO (2007) Table 11.5.6-1
res_sliding = 1
res_bearing = 0.65
res_tens_s = 0.75
res_pullout = 0.90
# Tabulating:
step_3_resistance_factors = (['Item','Resistance Factors'],
```

```
['Sliding on Foundation', "\u03A6{} = {}".format(get_sub('sl'), res_sliding)],
['Bearing Resistance', "\u03A6{} = {}".format(get_sub('br'), res_bearing)],
['Tensile Resistance (steel strip)', "\u03A6{} = {}".format(get_sub('ts'),
res_tens_s)],
['Tensile Resistance (geogrid)', "\u03A6{} = {}".format(get_sub('tg'),
res_tens_g)],
['Pullout Resistance', "\u03A6{} = {}".format(get_sub('pt'), res_pullout)])
t_s3_r = tb.tabulate(step_3_resistance_factors, headers ='firstrow', tablefmt =
'fancy_grid',numalign='center', stralign = 'center')
print("\n Applicable Load Factors from, AASHTO (2007) Tables 3.4.1-1 and
3.4.1-2", t_s3_f,"\nApplicable Resistance Factors, AASHTO (2007) Table
11.5.6.-1", t_s3_r, sep="\n")
```

Code 2.6 Un-factored loads and load factors

2.5. External Stability Control

This control step consider the wall as a whole structure and check the stability as it was done with conventional retaining walls. This step contains controls for sliding resistance, turnover resistance and bearing capacity. Note that, global stability has been excluded from this study as it was out of the scope, therefore its safety has been assumed to be adequate.

2.5.1. Sliding control

Un-factored load caused by retained soil resultant (F_t) is calculated as it is shown in previous section. Then, critical friction angle (ϕ_{cr}) which governs the sliding failure should be determined as it is shown in the Code 2.7. Therefore, the sliding control calculations are made with following sequence:

- Lateral load at MSE wall is, $H_m = F_{th}$
- Total vertical load at MSE base,

$$V_{a1} = V_1 + V_2 \tag{2.7}$$

$$V_{a2} = F_{tv} \tag{2.8}$$

$$V_a = V_{a1} + V_{a2} \tag{2.9}$$

- Total nominal sliding load at MSE base,

$$V_{n1} = tan\{\phi_{cr}\}(V_1 + V_2) \tag{2.10}$$

$$V_{n2} = tan\{\phi_{cr}\}(F_{tv}) \tag{2.11}$$

$$V_n = V_{n1} + V_{n2} \tag{2.12}$$

- Total factored sliding resistance on MSE wall base,

$$V_{f1} = \phi_{sl} V_{n1} \tag{2.13}$$

$$V_{f2} = \phi_{sl} V_{n2} \tag{2.14}$$

$$V_f = V_{f1} + V_{f2} \tag{2.15}$$

Note that, each calculation which contains resistance factor should be made for both maximum and the minimum value. Minimum calculated V_f should be greater than maximum calculated H_m, and thus Capacity/Demand Ratio (CDR) can be calculated as follows:

$$CDR = \frac{V_f(min)}{H_m(max)} \tag{2.16}$$

```
# Sliding Stability:
# 1: Retained backfil force resultant
print("Retained Soil Resultant per unit width (unfactored Ft):",Ft,"kN/m")
# 3: Determine the most critical frictional properties at the base. Choose
minimum phi for three possibilities below...
phi_cr = 0
if (coh_fnd + math.tan(math.radians(phi_fnd))) <
math.tan(math.radians(phi_wall)):
    phi_cr = phi_fnd # a: Sliding along the foundation soil
else phi_wall < phi_fnd and reinforcement_type = 'strip'
    phi_cr = phi_wall # b: Sliding along the reinforced fill
print("Critical fricition angle phi_cr:",phi_cr,"degree")
# 4: Resisting force
phi_cr_tan = math.tan(math.radians(phi_cr))
Ft_h_max = round((Ft_h*gama_EHmax),2)
Ft_h_min = round(Ft_h*gama_EHmin,2)
Va1_max = round(((V1+V2)*gama_EVmax),2)
Va1_min = round(((V1+V2)*gama_EVmin),2)
Va2_max = round((Ft_v*gama_EHmax),2)
Va2_min = round((Ft_v*gama_EHmin),2)
Va_max = round((Va1_max+Va2_max),2)
Va_min = round((Va1_min+Va2_min),2)
Vnm1_max = round((Va1_max*phi_cr_tan),2)
Vnm1_min = round((Va1_min*phi_cr_tan),2)
Vnm2_max = round((Va2_max*phi_cr_tan),2)
Vnm2_min = round((Va2_min*phi_cr_tan),2)
Vnm_max = round((Vnm1_max+Vnm2_max),2)
Vnm_min = round((Vnm1_min+Vnm2_min),2)
Vfm1_max = Vnm1_max * res_sliding
Vfm1_min = Vnm1_min * res_sliding
Vfm2_max = Vnm2_max * res_sliding
Vfm2_min = Vnm2_min * res_sliding
Vfm_max = Vfm1_max + Vfm2_max
```

```
Vfm_min = Vfm1_min + Vfm2_min
Vfmin = round((Vfm1_min + Vfm2_max),2)
#Tabulating:
step_4_sl = (['Item', 'Unit', 'Strength I (Max)','Strength I (Min)'],
['\033[1mHm = Ft_h\033[0m', 'kN/m', Ft_h_max, Ft_h_min],
['Va1 = V1+V2','kN/m', Va1_max, Va1_min],
['Va2 = Ft_v','kN/m', Va2_max, Va2_min],
['\033[1mVa=Va1+Va2\033[0m','kN/m', Va_max, Va_min],
['Vnm1 = tan(phi_cr)(V1+V2)','kN/m', Vnm1_max, Vnm1_min],
['Vnm2 = tan(phi_cr)(Ft_v)','kN/m', Vnm2_max, Vnm2_min],
['\033[1mVnm = Vnm1 + Vnm2\033[0m','kN/m', Vnm_max, Vnm_min],
['Vfm1 = \u03A6sl(Vnm1)','kN/m', Vfm1_max, Vfm1_min],
['Vfm2 = \u03A6sl(Vnm2)','kN/m', Vfm2_max, Vfm2_min],
['\033[1mVfm = Vfm1 + Vfm2\033[0m','kN/m', Vfm_max, Vfm_min],
['\033[1mIs Vfm > Hm?\033[0m','-', 'Yes\033[92m[SAFE]' if
Vfm_max>Ft_h_max else 'No \033[93m[NOT SAFE]',
 'Yes \033[92m[SAFE]\033[0m' if Vfm_min>Ft_h_min else 'No \033[93m[NOT
SAFE]\033[0m'],
['\033[1mCRITICAL VALUES BASED ON MAX/MIN','---','---','---\033[0m'],
['Vf (Vf_min)','kN/m', (Vfmin)],
['Hm (Hm_max)','kN/m', Ft_h_max],
['\033[1mIs Vf_min > Hm_max?\033[0m','-','Yes \033[92m[SAFE]\033[0m' if
(Vfm1_min + Vfm2_max)>Ft_h_max else 'No \033[93m[NOT SAFE]\033[0m'],
['\033[1mCDR = Vf_min/Hm_max\033[0m','-', round((Vfmin/Ft_h_max),2)])
t_s4_sl = tb.tabulate(step_4_sl, headers ='firstrow', tablefmt = 'fancy_grid',
                numalign='center', stralign = 'left')
print("\nComputations for Evaluation of Sliding Resistance of MSEW:\n",
t_s4_sl,
f"\nNote: For minimum Vf value, {Vfm1_min} + {Vfm2_max} = {Vfmin}.",
"\nThis is to maintain consistency between the total inclined lateral force and its
components.")
print("\033[1mPlease increase the reinforcement length and repeat the
calculation if CDR < 1\033[0m")
```

Code 2.7 Sliding stability check

2.5.2. Turnover Control

In the current LRFD method, the turnover control is made by checking the eccentricity limit. Un-factored moments are calculated as it was shown in Table 2.2, Table 2.3 and Code 2.6. Further calculations are made by using the calculated moment values, as follows:

- Total resisting moment about lower left-hand corner of MSE wall,

$$M_{r1} = M_{V_1} + M_{V_2} \tag{2.17}$$

$$M_{r2} = M_{F_{tv}} \tag{2.18}$$

$$M_r = M_{r1} + M_{r2} \quad (2.19)$$

- Total overturning moment about lower left-hand corner of MSE wall,

$$M_o = M_{F_{th}} \quad (2.20)$$

- Net moment value,

$$M_{net} = M_r - M_o > 0 \quad (2.21)$$

- Location of resultant force on base of MSE wall from lower left-hand corner,

$$X_r = \frac{M_{net}}{V_f} \quad (2.22)$$

- Eccentricity at base of the wall,

$$e_L = \frac{L}{2} - X_r \quad (2.23)$$

- Limiting eccentricity (for strength limit state),

$$e = \frac{L}{4} \quad (2.24)$$

- Actual eccentricity should be within limiting eccentricity,

$$e_L < e \quad (2.25)$$

The critical values based on max/min values should be chosen and the process above should be repeated as it is shown in the Code 2.8.

```
# It should be noted that the weight and width of the wall facing is neglected in the calculations.
print("\n\033[1m2. Eccentiricity Limit Check\033[0m")
Mra1_max = round(((mo1_v + mo2_v) * gama_EVmax), 2)
Mra1_min = round(((mo1_v + mo2_v) * gama_EVmin), 2)
Mra2_max = round((mo3_v * gama_EHmax), 2)
Mra2_min = round((mo3_v * gama_EHmin), 2)
Mra_max = round((Mra1_max + Mra2_max), 2)
Mra_min = round((Mra1_min + Mra2_min), 2)
Moa_max = round((mo1_h * gama_EHmax), 2)
Moa_min = round((mo1_h * gama_EHmin), 2)
Ma_max = round((Mra_max - Moa_max), 2)
Ma_min = round((Mra_min - Moa_min), 2)
a_max = round((Ma_max/Va_max), 2)
a_min = round((Ma_min/Va_min), 2)
eL_max = round(((L/2) - a_max),2)
eL_min = round(((L/2) - a_min),2)
ec = L/4
Mra_cr = round((Mra1_min+Mra2_max), 2)
Va_cr = round((Va1_min+Va2_max),2)
a_nl = round((Mra_cr/Va_cr),2)
```

```
e_L = round(((0.5*L) - a_nl),2)
B_prime = round((L - (2*e_L)),2) if e_L>0 else L
#Tabulating:
step_4_ecc = (['Item', 'Unit', 'Strength I (Max)','Strength I (Min)'],
['Vertical Load at MSEW Base, Va1 = V1+V2','kN/m', Va1_max, Va1_min],
['Vertical Load at MSEW Base, Va2 = Ft_v','kN/m', Va2_max, Va2_min],
['\033[1mTotal Vertical Load at MSE Base, Va=Va1+Va2\033[0m','kN/m',
Va_max, Va_min],
['Resisting Moments About Point A, Mra1 = MV1 + MV', 'kN-m/m', Mra1_max,
Mra1_min],
['Resisting Moments About Point A, Mra2 = MFt_v', 'kN-m/m', Mra2_max,
Mra2_min],
['Total Resisting Moments About Point A, Mra = Mra1 + Mra2', 'kN-m/m',
Mra_max, Mra_min],
['Overturning Moments about Point A, Moa = Ft_h', 'kN-m/m', Moa_max,
Moa_min],
['Net Moments about Point A, Ma = Mra - Moa', 'kN-m/m', Ma_max, Ma_min],
['Location of Resultant Force on base of MSEW from Point A, a = Ma/Va','m',
a_max, a_min],
['Eccentiricity at Base of MSEW, e_L = L/2 - a', 'm', eL_max, eL_min],
['Limiting Exxentiricity (for strength limit state), e = L/4','m', ec, ec],
['Is the Resultant within limiting value of e_L?', '-', 'Yes' if eL_max < ec else
'No','Yes' if eL_min < ec else 'No'],
['Calculated (e_L)/L value','-', round((eL_max/L),3), round((eL_min/L),3)],
['\033[1mCRITICAL VALUES BASED ON MAX/MIN','---','---','---\033[0m'],
['Overturning Moments About Point A, Moa-cr', 'kN-m/m',Moa_max],
['Resisting Moments About Point A, Mra-cr', 'kN-m/m', Mra_cr],
['Net Moment About Point A, Ma-cr = Mra-cr - Moa-cr','kN-m/m',
round((Mra_cr-Moa_max),2)],
['Vertical Force, Va-cr','kN/m',Va_cr],
['Location of Resultant from Point A, a_nl = Ma-cr/Va-cr','m', a_nl],
['Eccentricity from center of wall base, e_L = 0.5L - a_nl','m',
e_L if e_L >= 0 else f'{abs(e_L)} (-)'],
['Limiting eccentricity, e = L/4', 'm', ec],
['Is the limiting eccentricity criteria satisfied?', '-', 'Yes' if e_L < ec else 'No'],
["Effective width of base of MSEW, B'= L - 2e_L",'m', B_prime],
['Calculated e_L/L','-', round((abs(e_L)/L),2)])
t_s4_ec = tb.tabulate(step_4_ecc, headers = 'firstrow', tablefmt = 'fancy_grid',
stralign = 'center')
print("\nComputations for Evaluation of Turnover Resistance of MSEW:\n",
t_s4_ec,
f"\nNote: {Mra1_min} + {Mra2_max} = {Mra_cr}; {Va1_min} +
{Va2_max}={Va_cr}",
"\nThis is to maintain consistency between the total inclined lateral force and its
components.")
```

Code 2.8 Turnover Stability Check

2.5.3. Bearing Capacity Control

Herein this section, the significant equations for bearing capacity control and the Code which contains all steps to order the mentioned value are presented. The Code is presented in Code 2.9. The considered equations significantly related to this section are as follows:

- Effective width of base of MSE wall,

$$B' = L - 2e_L \tag{2.26}$$

- Bearing stress to be checked,

$$\sigma_v = \frac{V_f}{B'} \tag{2.27}$$

- Factored bearing resistance should be greater than bearing stress,

$$\sigma_r > \sigma_v \tag{2.28}$$

- Capacity/Demand Ratio (CDR),

$$CDR = \frac{\sigma_r}{\sigma_v} \tag{2.29}$$

```
# Bearing Capacity of Foundation
print("\n\033[1m3. Bearing on Foundation Check\033[0m")
print("General Shear Failure Check")
# Nominal bearing resistance, qn
# Nc and N_gamma = dimensionless bearing capacity coefficients
phi = [0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,
16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,
31,32,33,34,35,36,37,38,39,40,41,42,43,44,45]
Nc = [5.14,5.4,5.6,5.9,6.2,6.5,6.8,7.2,7.5,7.9,8.4,
8.8,9.3,9.8,10.4,11.0,11.6,12.3,13.1,13.9,14.8,15.8,
16.9,18.1,19.3,20.7,22.3,23.9,25.8,27.9,30.1,32.7,35.5,
38.6,42.2,46.1,50.6,55.6,61.4,37.9,75.3,83.9,93.7,105.1,
118.4,133.9]
N_gama = [0.0,0.1,0.2,0.2,0.3,0.5,0.6,0.7,0.9,1.0,1.2,1.4,1.7,
2.0,2.3,2.7,3.1,3.5,4.1,4.7,5.4,6.2,7.1,8.2,9.4,10.9,12.5,14.5,
16.7,19.3,22.4,25.9,30.2,35.2,41.1,48.0,56.3,66.2,78.0,92.3,
109.4,130.2,155.6,186.5,224.6,271.8]
ind = phi.index(phi_fnd) # find the index number of phi_fnd in phi list
NNc = Nc[ind] # Use same index number to get corresponding Nc
NN_gama = N_gama[ind] # Use same index number to get corresponding
N_gama
```

```
# Since all the factors of Service Limit State is 1.00, it is not mentioned in the
calculations below:
Vab1 = round((V1+V2),2)
Vab2 = round(Ft_v,2)
R_ab = round((Vab1+Vab2),2)
Mra1_ser = round((mo1_v + mo2_v), 2)
Mra2_ser = round(mo3_v, 2)
Mra_ser = round((Mra1_ser + Mra2_ser), 2)
Moa_ser = round(mo1_h, 2)
Ma_ser = round((Mra_ser - Moa_ser), 2)
a_ser = round((Ma_ser/R_ab), 2)
eL_ser = round(((L/2) - a_ser),2)
ec_ser = round((L/6),2) # it was L/4 for Str I and II combinations
Bp_max = round(L - (2*eL_max),2)
Bp_min = round(L - (2*eL_min),2)
Bp_ser = round(L - (2*eL_ser),2)
q_v_br_max = round((Va_max/Bp_max),2)
q_v_br_min = round((Va_min/Bp_min),2)
q_v_br_ser = round((R_ab/Bp_ser),2)
eb_max = a_max
eb_min = a_min
eb_ser = a_ser
L_efec_max = (L - 2*eb_max) if (L - 2*eb_max)>0 else L #FHWA V.1 4-22 ->
L_prime
L_efec_min = (L - 2*eb_min) if (L - 2*eb_min)>0 else L
L_efec_ser = (L - 2*eb_ser) if (L - 2*eb_ser)>0 else L
qn_max = round((coh_fnd * NNc + 0.5 * L_efec_max * BHA_fnd * NN_gama),
2) # kN/m2
qn_min = round((coh_fnd * NNc + 0.5 * L_efec_min * BHA_fnd * NN_gama),
2) # kN/m2
qn_ser = round((coh_fnd * NNc + 0.5 * L_efec_ser * BHA_fnd * NN_gama), 2)
# kN/m2
qr_max = round((res_bearing * qn_max), 2) # 0.65 is a factor for bearing
resistance - Table 11.5.6-1, AASHTO {2007}
qr_min = round((res_bearing * qn_min), 2)
qr_ser = round((res_bearing * qn_ser), 2)
a_br_nl = round(((Mra_cr-Moa_max)/Va_cr),2)
e_L_br = round((0.5*L - a_br_nl),2)
B_br_prime = round((L - (2*e_L_br)),2) if e_L_br>0 else L
#Tabulating:
step_4_br = (['Item', 'Unit', 'Strength I (Max)','Strength I (Min)', 'Ser. Lim.'],
['Vertical Load at MSEW Base, \nVab1 = V1+V2','kN/m', Va1_max, Va1_min,
Vab1],
['Vertical Load at MSEW Base, \nVab2 = Ft_v','kN/m', Va2_max, Va2_min,
Vab2],
['\033[1mTotal Vertical Load \nat MSE Base, Rab=Va1+Va2\033[0m','kN/m',
Va_max, Va_min,R_ab],
['Resisting Moments About Point A, \nMra1 = MV1 + MV2', 'kN-m/m',
Mra1_max, Mra1_min, Mra1_ser],
```

```
['Resisting Moments About Point A, \nMra2 = MFt_v', 'kN-m/m', Mra2_max,
Mra2_min, Mra2_ser],
['Total Resisting Moments About Point A, \nMra = Mra1 + Mra2', 'kN-m/m',
Mra_max, Mra_min, Mra_ser],
['Overturning Moments about Point A, \nMoa = Ft_h', 'kN-m/m', Moa_max,
Moa_min, Moa_ser],
['Net Moments about Point A, \nMa = Mra - Moa', 'kN-m/m', Ma_max, Ma_min,
Ma_ser],
['Location of Resultant Force \non base of MSEW from Point A, \na = Ma/Va','m',
a_max, a_min, a_ser],
['Eccentiricity at Base of MSEW, \ne_L = L/2 - a', 'm', eL_max, eL_min, eL_ser],
['Limiting Exxentiricity \ne = L/4 (Str I&II), \nL/6 (Ser. Lim.)','m', ec, ec, ec_ser],
['Is the Resultant within \nlimiting value of e_L?', '-', 'Yes' if eL_max < ec else
'No',
'Yes' if eL_min < ec else 'No', 'Yes' if eL_ser < ec_ser else 'No'],
["Effective width of \nbase of MSEW, \nB'= L - 2e_L",'m', Bp_max, Bp_min,
Bp_ser],
["Bearing Stress, \nq_v = Rab / B'",'kN/m2',q_v_br_max, q_v_br_min,
q_v_br_ser],
['Factored Bearing Resistance, \nqr (qnf)','kN/m2', qr_max, qr_min, qr_ser],
['Capacity:Demand Ratio \n(CDR), qr/q_v','-',round((qr_max/q_v_br_max),2),
round((qr_min/q_v_br_min),2),round((qr_ser/q_v_br_ser),2)],
['\033[1mCRITICAL VALUES BASED ON MAX/MIN','---','---','---\033[0m'],
['Overturning Moments About Point A, \nMoa-cr', 'kN-m/m',Moa_max],
['Resisting Moments About Point A, \nMra-cr', 'kN-m/m', Mra_cr],
['Net Moment About Point A, \nMa-cr = Mra-cr - Moa-cr','kN-m/m',
round((Mra_cr-Moa_max),2)],
['Vertical Force, Rab-cr','kN/m',Va_cr],
['Location of Resultant from Point A, \na_br_nl = Ma-cr/Rab-cr','m', a_br_nl],
['Eccentricity from center of wall base, \ne_L = 0.5L - a_br_nl','m',
e_L_br if e_L_br >= 0 else f'{abs(e_L_br)} (-)'],
['Limiting eccentricity, \ne = L/4', 'm', ec],
['Is the limiting eccentricity criteria satisfied?', '-', 'Yes' if e_L_br < ec else 'No'],
["Effective width of base of MSEW, \nB'= L - 2e_L",'m', B_br_prime if e_L_br>0
else f'{L} (= L)\n(Because e_L is negative)'],
['Bearing Stress (Critical),\nq_v(cr) = Rab-cr / B','kN-
m/m',round((Va_cr/B_br_prime),2)],
['Factored Bearing Resistance, \nqr (qnf)','kN/m2', max(qr_max, qr_min, qr_ser)],
['Is Bearing Stress < Factored Bearing Resistance','-',
'Yes' if round((Va_cr/B_br_prime),2)<max(qr_max, qr_min, qr_ser) else 'No'],
['Capacity:Demand Ratio \n(CDR), qr/q_v(cr)','-',round((max(qr_max, qr_min,
qr_ser))/(Va_cr/B_br_prime),2)])
t_s4_br = tb.tabulate(step_4_br, headers = 'firstrow', tablefmt = 'fancy_grid',
stralign = 'center')
print("Bearing Capacity Check:", t_s4_br, sep="\n")
```

Code 2.9 Bearing capacity check

2.6. Internal Stability Controls

Internal stability controls are the second main stage of stability controls for MSE walls. In addition to that, this stage is specifically about MSE walls as a distinguishing check for the reinforcement within the wall structure. Tensile and pullout controls are the main failure modes to be checked herein. For preliminary calculations, height of wall from top of the failure surface (i.e. effective height), slip surface angle and active earth pressure coefficient (K_a) are obtained. In addition, sloping backfill transformed to an equivalent uniform height for the simplification of calculation process. The preliminary codes for further calculations is shown in Code 2.10.

```
print("Step 5:","\n\033[1mINTERNAL STABILITY CHECK\n\033[0m")
Z = np.arange(R_v, 5, R_v) # array for reinforcement levels (top, bottom,
spacing)
Z = np.round(Z,2)
q_H = np.array([]) # array for lateral pressure of each reinforcement level
Tmax = np.array([]) # array for maximum factored tension Tmax
Z_minus = np.array([]) # array for the starting depth of contributory depth
Z_positive = np.array([]) # array for the finishing depth of contributory depth
Sv = np.array([]) # array for contributory depth of reinforcements
```

Code 2.10 Array construction for internal stability

Estimation of failure surface depends on the reinforcement type. The anticipated failure surface for strip type of element is presented in Fig.2.2 which is based on The American Association of State Highway and Transportation Officials (AASHTO, 2010).

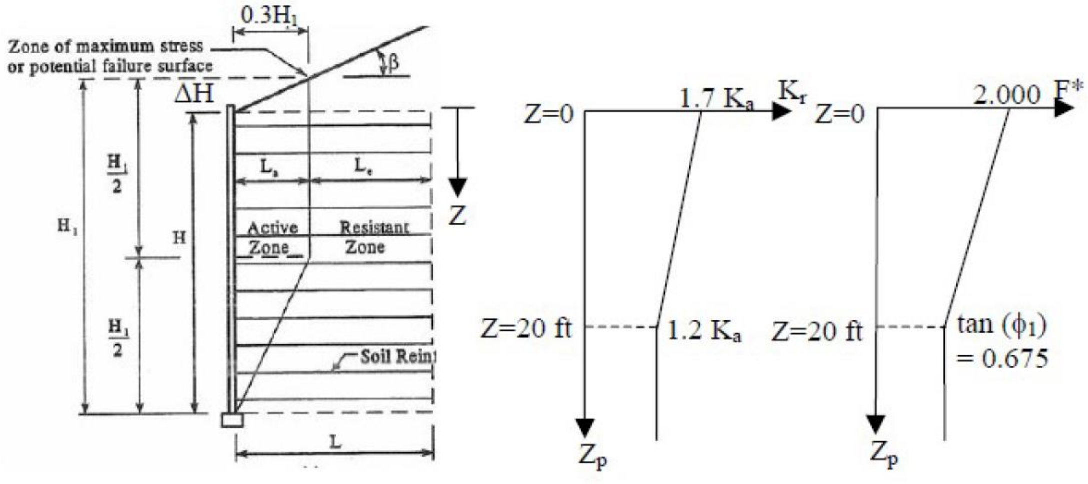

Figure 2.2 Potential failure surface and graphs to calculate required equation

Further calculations are made in following sequence:

- Equivalent uniform height of the soil,

$$S_{eq} = \frac{1}{2} 0.7 H tan\beta \tag{2.30}$$

- Uniform load on reinforced zone,

$$\sigma_2 = S_{eq}\gamma_b \tag{2.31}$$

where γ_b is the unit weight of the soil of reinforced zone. In addition to those equations above, relevant calculation steps are presented in Code 2.11. Reinforcement placement is a matter of design decision. In this study, for the purpose of having variation of strip amounts in each reinforcement layer, vertical spacing between reinforcement levels have been kept relatively longer. Contributory area (S_v) that is the area where lateral loads are applied, is shown in the Table 2.6.

Table 2.6 Computation Steps of Contributory Area, Sv

Level	**Z (depth)(m)**	**Z(-)(m)**	**Z(+)(m)**	**S_v (m)**
1	0.8	0.0	1.2	1.2
2	1.6	1.2	2.0	0.8
3	2.4	2.0	2.8	0.8
4	3.2	2.8	3.6	0.8
5	4.0	3.6	4.4	0.8
6	4.8	4.4	5.0	0.6

```
reinforcement_type == 'strip':
#h_slip: effective height of the wall
h_slip = round(H + ((math.tan(math.radians(beta)) * 0.3 * H)/(1 - (0.3 *
math.tan(math.radians(beta))))), 2)
print("Height of wall at the top of slip surface (h_slip) is {} m".format(h_slip))
#angle of critical surface until h_slip/2 height from bottom of vertical wall face
w1 = 90 - 31 # 90 - arctan(0.3*h_slip/0.5*h_slip) = 31 degree
print("Slip Surface Angle (w) is:\033[1m {} degree from ground to slip
surface\033[0m up to {} m height".format(w1,(h_slip/2)))
print("And \033[1m{} degree from wall to slip surface\033[0m".format(90-w1))
w2 = 90 # The slip surface angle from height of h_slip/2 to h_slip is 90 degree for
metal strip reinforcement
print("The slip surface angle from height of {} m to {} m is 90 degree (as the
reinforcement type is metal strip)".format((h_slip/2),h_slip))
Ka = round(math.tan(math.radians(45-(phi_wall/2)))**2, 3)
print("Rankine active earth pressure coefficient (Ka):",Ka)
S_eq = round(0.5*0.7*H*math.tan(math.radians(beta)),3) # equivalent uniform
height of soil
q2 = round(S_eq * BHA_wall,3) # kN/m2
```

```
print("Equivalent uniform height of soil (Seq):",S_eq,"m")
print("Uniform Load on Reinforcement (\u03C3_2):",q2,"kN/m2")
             for i in range(len(Z)):
        #The equation below for Kr is obtained from the Figure 4-10 of FHWA
Volume I (linear interpolation)
        if H <= 6:
            # Here the horizontal stress is computed at any given level of
reinforcement;
            if i == 0:
                Kr = ((0.5*Ka*(6-Z[i]))/6)+(1.2*Ka)
                P_lateral = round(Kr*(BHA_wall * (Z[i] + S_eq) * gama_EVmax), 3)
                q_H = np.append(q_H, [P_lateral])

            elif i<(len(Z)-1):
                Kr_m = ((0.5*Ka*(6-Z[i-1]))/6)+(1.2*Ka)
                P_lateral_m = round(Kr_m*(BHA_wall * (Z[i-1] + S_eq) *
gama_EVmax), 3)

                Kr_p = ((0.5*Ka*(6-Z[i+1]))/6)+(1.2*Ka)
                P_lateral_p = round(Kr_p*(BHA_wall * (Z[i+1] + S_eq) *
gama_EVmax), 3)

                P_lateral = 0.5 * (P_lateral_m + P_lateral_p)
                q_H = np.append(q_H, [P_lateral])

            else:
                Kr_m = ((0.5*Ka*(6-Z[i-1]))/6)+(1.2*Ka)
                P_lateral_m = round(Kr_m*(BHA_wall * (Z[i-1] + S_eq) *
gama_EVmax), 3)

                Kr_p = ((0.5*Ka*(6-H))/6)+(1.2*Ka)
                P_lateral_p = round(Kr_p*(BHA_wall * (H + S_eq) * gama_EVmax),
3)

                P_lateral = 0.5 * (P_lateral_m + P_lateral_p)
                q_H = np.append(q_H, [P_lateral])
        else:
            Kr = 1.2*Ka # Not required for this particular study

        # Then the maximum tension, Tmax, is computed as follows:
        # Here wall is designed with the height of 5 m. This calculation must be
modified once height is changed.
        if i == 0:
            Z_m_top = 0
            Z_p_top = Z[i] + 0.5*(Z[i+1]-Z[i])
            top_Sv = Z_p_top - Z_m_top
            Z_minus = np.append(Z_minus, [Z_m_top])
            Z_positive = np.append(Z_positive, [Z_p_top])
            Sv = np.append(Sv, [top_Sv])
            Tm = round((P_lateral * (top_Sv*wp)), 3) # Atrib = top_Sv*wp
```

```
    elif i == (len(Z)-1):
        Z_m_bottom = Z[i] - 0.5*(Z[i]-Z[i-1])
        Z_p_bottom = H
        bottom_Sv = Z_p_bottom - Z_m_bottom
        Z_minus = np.append(Z_minus, [Z_m_bottom])
        Z_positive = np.append(Z_positive, [Z_p_bottom])
        Sv = np.append(Sv, [bottom_Sv])
        Tm = round((P_lateral * (bottom_Sv*wp)), 3) # Atrib = bottom_Sv*wp
    else:
        Z_m_mid = Z[i] - 0.5*(Z[i]-Z[i-1])
        Z_p_mid = Z[i] + 0.5*(Z[i+1]-Z[i])
        Mid_Sv = Z_p_mid - Z_m_mid
        Z_minus = np.append(Z_minus, [Z_m_mid])
        Z_positive = np.append(Z_positive, [Z_p_mid])
        Sv = np.append(Sv, [Mid_Sv])
        Tm = round((P_lateral * (Mid_Sv*wp)), 3) # Atrib = Mid_Sv*wp

    Tmax = np.append(Tmax, [Tm])
    print(f'{i+1}. re. layer {Z[i]}m {round((Z_minus[i]),2)} = Z (-)/
{round((Z_positive[i]),2)} = Z (+) / Sv = {round((Sv[i]),2)} m ')
```

Code 2.11 Initial calculations for internal stability

2.6.1. Tensile Failure Control

Main concern for long term tensile failure mode is the decrease in strip crosssectional area due to corrosion. The American Association of State Highway and Transportation Officials (AASHTO, 2010) neglects the cut edge corrosion for this particular step as its effect is insignificant. The base line case assumed to have a soil type with electrochemical properties as it is previously shown in Table 2.1. Relevant Code is presented in Code 2.12.

```
zinc_2 = 0.015 # mm per year is the lose of zinc for first two years - 11.10.6.4.2a AASHTO (2007)
zinc_los = 0.004 # mm per year for subsequent years
steel_los = 0.012 # mm per year/side
life_zinc = round((2 + ((zinc_t1 - 2*zinc_2)/zinc_los)),2)
life_zinc_r = math.floor(2 + ((zinc_t1 - 2*zinc_2)/zinc_los)) # years will be with zinc coverage
design_life_r = round((design_life - life_zinc_r),2) # years will remain without zinc coverage
strip_los = round((design_life_r * steel_los * 2),2) # mm until the end (2 is here because there are
two active sides of strip)
strip_thickness_r = round((strip_thickness - strip_los),2) # mm
strip_area = round((strip_thickness_r * strip_width),2) # mm2 - after corrosion
```

Code 2.12 Input for corrosion effect

The allowable tensile strength (T_{al}) is calculated as follows:

$$T_{al} = T_{ult} A_{strip} n_{strip} \tag{2.32}$$

where T_{ult} = the ultimate tensile strength of a strip element, A_{strip} = crosssectional area of strip element and nstrip = strip amount in related reinforcement layer. In this regard, tensile resistance (T_r) is equal to factored allowable tensile strength (T_{ult}) by resistance factor (ϕ_{ts}) which was previously presented in Table 2.5, and it is calculated as follows:

$$T_r = T_{ult}\phi_{ts} \tag{2.33}$$

```
Tal = round((Tult * 0.001 * strip_area * n_strip),2) # MPa * mm2 = 0.001*kN/m2
r_phi = 0.75 # Resistance factor
Tr = round(r_phi * Tal, 3) # Tension resistance
a_sc = 1 # a scale effect correction factor (generally 1.0 for metallic
reinforcements)
C = 2 # Unit perimeter factor - 2 for strip reinforcement.
#Tabulating:
rein_res = (['Item', 'Time', 'Value'],
['Lose of zinc (firs 2 years)','per year',f'{zinc_2} mm'],
['Lose of zinc (subsequent years)','per year',f'{zinc_los} mm'],
['Lifetime of zinc','years',f'{life_zinc} ~ {life_zinc_r}'],
['Remaning design life','years', design_life_r],
['Lose of steel','per year', f'{steel_los} mm'],
['Remaining cross section \nof steel strip',' - ', f'{strip_area} mm2'],
['T_allowable',' - ',f'{Tal} kN'],
['T_resistance \n(factored T_allowable)',' - ', f'{Tr} kN\n{n_strip}
strips\n({round((Tr/n_strip),2)} kN \nper each strip)'])
t_rein_res = tb.tabulate(rein_res, headers = 'firstrow', tablefmt = 'fancy_grid',
stralign = 'center')
print("Tension Resistance for Steel Strip:", t_rein_res, sep="\n")
#Safety indicator:
    for i in range(len(Z)):

        if Tr > Tmax[i]:
            print(f"For {i}. level at {Z[i]} m from top: Tr = {Tr} (kN-{n_strip} strip)
> {Tmax[i]} kN = Tmax \033[1m\033[92m[SAFE]\033[0m")
        elif Tr < Tmax[i]:
            print(f"For {i}. level at {Z[i]} m from top: Tr = {Tr} (kN-{n_strip} strip)
< {Tmax[i]} kN = Tmax \033[1m\033[93m[NOT SAFE]\033[0m")
        else:
            print(f"For {i}. level at {Z[i]} m from top: Tr = {Tr} (kN-{n_strip} strip)
= {Tmax[i]} kN = Tmax \033[1m\033[93m[NOT SAFE]\033[0m")
```

Code 2.13 Tension failure check

2.6.2. Pullout Failure Control

Pullout failure is the main focus point of this study. It depends on mainly two aspects which are pullout criteria length (L_{pcr}) and pullout resistant per reinforce ment element

(P_r), respectively. L_{pcr} is the minimum amount of reinforcement length which should be placed in resistant zone within structure. These parameters are calculated as follows:

$$\phi L_e \geq \frac{T_{max}}{F^* \alpha \sigma_v C R_c} \tag{2.34}$$

and hence,

$$L_{pcr} = \frac{T_{max}}{\phi F^* \alpha \sigma_v C R_c} \tag{2.35}$$

and,

$$L_e \geq L_{pcr} \tag{2.36}$$

and pullout resistance per unit width of reinforcement element,

$$P_{res} = \alpha F^* C b L_e \sigma_v \tag{2.37}$$

where L_e = effective length of the reinforcement, T_{max} = maximum tensile load, F^* = pullout factor, α = scale factor, σ_v = vertical stress, R_c = Coverage ratio ($R_c = b/S_h$, where b = width of the reinforcement strip element, S_h = center-tocenter horizontal space between reinforcement elements), C = surface area factor (= 2), ϕ = pullout resistance factor. In this regard, preliminary arrays and the pullout factor value are defined as it is shown in the Code 2.14, in order to be used later on for related parameters.

```
q_Vpo = np.array([]) # Unfactored vertical stress at the reinforcement level in the
resistant zone
La = np.array([]) # Active reinforcement length
Le = np.array([]) # Effective reinforcement length, in resistant zone
Zslope = np.array([]) # depth from top of slope to top of reinforced zone for
pullout check
Zp = np.array([]) # overall depth from top of slope to top of reinforcement to be
checked for pullout
r_phi_p = 0.9 # pullout resistance factor
h_slip_modified = H - (0.5*h_slip) # height of the vertical part of slip surface
within reinforced zone
Pr_p = np.array([])
Nt = np.array([]) # determination of number of reinforcements in each layer with
regard to Tmax
Np = np.array([]) # determination of number of reinforcements in each layer with
regard to Pr
```

Code 2.14 Array construction for pullout check

The constructed ”for” loop in order to calculate L_{pcr} is shown in Code 2.15.

```
for i in range(len(Z)):
    #The equation below for F_r is obtained from the Eq. 3-4 and 3-5 of FHWA
Volume I (linear interpolation)
    if H <= 6:
        F_r = (((1.8-math.tan(math.radians(phi_wall)))*(6-Z[i]))/6) +
math.tan(math.radians(phi_wall))
        # This is the value of pullout resistance factor F*
    else:
        F_r = math.tan(math.radians(phi_wall))

    if Z[i] <= h_slip_modified: # vertical part of slip surface
        L_a = round((0.3 * h_slip), 2) # m
        L_e = round((len_reinf_min - L_a),2) # m
    else: # inclined part of slip surface
        L_a = round(math.tan(math.radians(90 - w1))*(H - Z[i]), 2) # m
        L_e = round((len_reinf_min - L_a),2) # m

    La = np.append(La, [L_a]); Le = np.append(Le, [L_e]) # m
    Z_slope = round((L_a * (L_e/2)) * math.tan(math.radians(beta)),2) # m
    Zslope = np.append(Zslope, [Z_slope]) # m
    Zp = np.append(Zp, [Z[i]+Z_slope]) # m
    q_Vpo = np.append(q_Vpo, [Zp[i]*BHA_wall]) # kPa

    pullout_criteria = round((Tmax[i])/(r_phi_p * F_r * a_sc * q_Vpo[i] * C *
Rc), 2)

    if Le[i] < 1:
        print(50*".")
        print(f'{i}. layer from top: Le {Le[i]} m < 1 m (Le_min)
\033[1m\033[93m[NOT SAFE: Increase the length of reinforcement]\033[0m')
    elif Le[i] <= pullout_criteria: # (11.10.6.3.2-1) AASHTO (2007)
        print(f'{i}. layer from top: Le {Le[i]} m < {pullout_criteria} m (Pullout
Criteria) \033[1m\033[93m[NOT SAFE: Increase the length of
reinforcement]\033[0m')
    else:
        print(50*".")
        print(f"For {i}. layer from top: La = {La[i]} m and  Le = {Le[i]} m
\033[1m\033[92m[SAFE]\033[0m")
        print(f"{Le[i]} > {pullout_criteria} m (pullout_criteria) and 1 m
(Le_min)")
```

Code 2.15 Pullout criteria length calculation

The constructed ”for” loop in order to calculate Pr, governing factor for strip reinforcement element amount and the required amount of reinforcement strip elements is shown in Code 2.16. It should be noted that the calculation step for the required number of strip elements mainly depends on the decimal value of calculated strip element amount. This phenomena will be the governing when it comes to after corrosion stage for required amount of strip elements.

```
for n in range(len(Z)):
        # (Pr = F* . a . q_v . C. Le ) is the ultimate pullout resistance Pr per unit of reinforcement width.
        # in the Pr_pullout eq. below, 'b' is involved for obtaining the pullout resistance per strip.
        Pr_pullout = round((a_sc * F_r * C * b * Le[n] * q_Vpo[n]),2)
        Pr_p = np.append(Pr_p, [Pr_pullout])
        # Pr_pullout_r = round((a_sc * F_r * C * (strip_width_r*0.001) * Le[i] * q_Vpo[i]),2)
        Ntt = round((Tmax[n]/Tr),2)
        Npr = round((Tmax[n]/Pr_p[n]),2)
        Npr_ceiled = math.ceil(Npr)
        Np = np.append(Np, [Npr_ceiled]) # array for required number of strips with regard to pullout failure

        if Ntt > Npr:
            print(50*"-")
            print(f"For {n}. layer at {Z[n]} m from top:\n")
            print(f'Pr values: {n} -> {Pr_p[n]}')
            print(f"Nt = {Ntt} (strips) > Np = {Npr} (strips) (Rupture Failure Governs)")
            print(f'{math.ceil(Ntt)} strips are needed in this layer')
            print(f"(There is/are {n_strip} strip/s in this layer)")
            if math.ceil(Ntt) <= n_strip:
                print( "\033[1m\033[92m[SAFE]\033[0m")
            elif math.ceil(Ntt) > n_strip:
                print("\033[1m\033[93m[NOT SAFE]\033[0m")
        elif Ntt < Npr:
            print(50*"-")
            print(f"For {n}. layer at {Z[n]} m from top:\n")
            print(f'Pr values: {n} -> {Pr_p[n]}')
            print(f"Nt = {Ntt} (strips) < Np = {Npr} (strips) (Pullout Failure Governs)")
            print(f'{math.ceil(Npr)} strips are needed in this layer')
            print(f"(There is/are {n_strip} strip/s in this layer)")
            if math.ceil(Npr) <= n_strip:
                print( "\033[1m\033[92m[SAFE]\033[0m")
            elif math.ceil(Npr) > n_strip:
                print("\033[1m\033[93m[NOT SAFE]\033[0m")
        else:
            print(50*"-")
            print(f"For {n}. layer at {Z[n]} m from top:\n")
            print(f'Pr values: {n} -> {Pr_p[n]}')
            print(f"Nt = {Ntt} (strips) = Np = {Npr} (strips) ")
            print(f'{math.ceil(Npr)} strips are needed in this layer')
            print(f"(There is/are {n_strip} strip/s in this layer)")
```

```
            if math.ceil(Npr) == n_strip:
                print( "\033[1m\033[92m[SAFE]\033[0m")
            elif math.ceil(Npr) > n_strip:
                print("\033[1m\033[93m[NOT SAFE]\033[0m")
```

Code 2.16 Pullout resistance per unit width of reinforcement

2.7. Parametric Study Components

Herein this study, a parametric study is conducted by changing the S_h values, considering two kinds of b which are strip width at the design stage (b_i) and after corrosion (b_f). Pullout criteria length and pullout resistance per strip width are investigated in order to observe the general pullout behaviour. The base line case is made as it is previously described, and parametric study is conducted on the base of two defined python codes which are shown in Code 2.17 and Code 2.18.

2.7.1. Center-to-Center Horizontal Spacing

The center-to-center horizontal spacing, S_h, is a governing component of the coverage ratio, R_c, and therefore any change in S_h results with a change in R_c. The Code which is shown in Code 2.17 has been constructed in order to have a reasonable application of different S_h values. The panel width, w_p, is taken a constant value and represents the boundaries of implication area. S_h values has been changed by the increments of strip width, b. A”for loop” is constructed to imply differing S_h values and all the results are stored in arrays. Those values within arrays are later on printed in an excel file in order to be used and presented in graphs.

```
def sh_change():
    workbook = xl.Workbook('D:/sh_change.xlsx')
    worksheet = workbook.add_worksheet('Sh Change vs Pullout Criteria')
    b = 0.05
    wp = 1.5
    row = 1
    col = 1
    roa = 0
    coa = 2
    roo = 1
    coo = 2
    Z = np.arange(R_v, 5, R_v) # array for reinforcement levels (top, bottom,
spacing)
    Z = np.round(Z,2)
```

```
    q_Vpo = np.array([]) # Nominal (i.e., unfactored) vertical stress at the
reinforcement level in the resistant zone
    La = np.array([])
    Le = np.array([])
    Zslope = np.array([]) # depth from top of slope to top of reinforced zone for
pullout check
    Zp = np.array([]) # overall depth from top of slope to top of reinforcement to
be checked for pullout
    r_phi_p = 0.9
    Pr_p = np.array([])
    for i in range(len(Z)):
        rc_array = np.arange(b, (wp-b)/(Np[i]-1),b)
        h_slip_modified = H - (0.5*h_slip) # height of the vertical part of slip
surface within reinforced zone
        F_r = (((1.8-math.tan(math.radians(phi_wall)))*(6-Z[i]))/6) +
math.tan(math.radians(phi_wall))
        # This is the value of pullout resistance factor F*
        if Z[i] <= h_slip_modified: # vertical part of slip surface
            L_a = round((0.3 * h_slip), 2) # m
            L_e = round((len_reinf_min - L_a),2) # m
        else: # inclined part of slip surface
            L_a = round(math.tan(math.radians(90 - w1))*(H - Z[i]), 2) # m
            L_e = round((len_reinf_min - L_a),2) # m
        La = np.append(La, [L_a]); Le = np.append(Le, [L_e]) # m
        Z_slope = round((L_a * (L_e/2)) * math.tan(math.radians(beta)),2) # m
        Zslope = np.append(Zslope, [Z_slope]) # m
        Zp = np.append(Zp, [Z[i]+Z_slope]) # m
        q_Vpo = np.append(q_Vpo, [Zp[i]*BHA_wall]) # kPa
        for j in range(len(rc_array)):
            worksheet.write(roa, coa, rc_array[j])
            Rc_A = b/rc_array[j]
            pullout_criteria = round((Tmax[i])/(r_phi_p * F_r * a_sc * q_Vpo[i] * C
* Rc_A), 2)
            # (Pr = F* . a . \sigma_v . C. Le ) is the ultimate pullout resistance Pr per
unit of reinforcement width.
            # in the Pr_pullout eq. below, 'b' is involved for obtaining the pullout
resistance per strip.
            Pr_pullout = round((a_sc * F_r * C * b * Le[i] * q_Vpo[i]),2)
            Pr_p = np.append(Pr_p, [Pr_pullout])
            Ntt = round((Tmax[i]/Tr),2)
            Npr = round((Tmax[i]/Pr_p[i]),2)
            worksheet.write(roo, coo, pullout_criteria)
            #worksheet.write(roo + len(Z), coo, Pr_pullout)
            #worksheet.write(roo + (len(Z)*2), coo, math.ceil(Npr))
            coa += 1
            coo += 1
        coa = 2
        coo = 2
        roa += 3
        roo += 3
```

```
    for i in range(len(Z)):
        worksheet.write(row, col, Le[i])
        worksheet.write(row, col-1, Np[i])
        row += 3
    workbook.close()
    return
```

Code 2.17 Application of different Sh values and writing results to an excel file

2.7.2. The Cut Edge Corrosion Effect

The cut edge corrosion is a mostly neglected issue when it comes to MSE walls with steel strip reinforcement. This is because of their negligible effect to tension failure. In order to observe their effect to the pullout behaviour of the MSE wall, the Code which is shown in Code 2.18 is constructed. Results are printed into an excel file in order to be used and visualised later on.

```
def Presistance():
    workbook = xl.Workbook('D:/Presistance.xlsx')
    worksheet = workbook.add_worksheet('Pr Nstrip b relations')
    row = 1
    col = 1
    zinc_t1 = 0.086 # mm - on up and down sides of strip
    zinc_t2 = 0 # mm - on left and right sides of strip - in order to calculate worse
condition
    strip_thickness = 4 # mm
    strip_width = 50 # mm
    zinc_2 = 0.015 # mm per year is the lose of zinc for first two years -
11.10.6.4.2a AASHTO (2007)
    zinc_los = 0.004 # mm per year for subsequent years
    steel_los = 0.012 # mm per year/side
    life_zinc = round((2 + ((zinc_t1 - 2*zinc_2)/zinc_los)),2)
    life_zinc_r = math.floor(2 + ((zinc_t1 - 2*zinc_2)/zinc_los)) # years will be
with zinc coverage
    design_life_r = round((design_life - life_zinc_r),2) # years will remain without
zinc coverage
    strip_los = round((design_life_r * steel_los * 2),2) # mm until the end (2 is here
because there are two active sides of                    strip)
    strip_thickness_r = round((strip_thickness - strip_los),2) # mm
    #ZINC THICKNESS ON LEFT AND RIGHT IS ZERO:
    life_zinc_r_s = 0
    design_life_r_s = round((design_life - life_zinc_r_s),2) # years will remain
without zinc coverage
    strip_los_s = round((design_life_r_s * steel_los * 2),2) # mm until the end (2 is
here because there are two active sides of                  strip)
    strip_width_r = round((strip_width - strip_los_s),2) # mm
    for n in range(len(Z)):
```

```
        # (Pr = F* . a . \sigma_v . C. Le ) is the ultimate pullout resistance Pr per unit of reinforcement width.
        # in the Pr_pullout eq. below, 'b' is involved for obtaining the pullout resistance per strip.
        Pr_pullout = round((a_sc * F_r * C * b * Le[n] * q_Vpo[n]),2)
        Pr_pullout_r = round((a_sc * F_r * C * (strip_width_r*0.001) * Le[n] * q_Vpo[n]),2)
        Npr_r = round((Tmax[n]/Pr_pullout_r),2)
        Npr_r_ceiled = math.ceil(Npr_r)
        Npr = round((Tmax[n]/Pr_pullout),2)
        Npr_ceiled = math.ceil(Npr)
        worksheet.write(row, col, b)
        worksheet.write(row, col+1, Le[n])
        worksheet.write(row, col+2, Pr_pullout)
        worksheet.write(row, col+3, Npr_ceiled)
        worksheet.write(row, col+4, Npr)
        worksheet.write(row, col+7, round((strip_width_r*0.001),4))
        worksheet.write(row, col+8, Le[n])
        worksheet.write(row, col+9, Pr_pullout_r)
        worksheet.write(row, col+10, Npr_r_ceiled)
        worksheet.write(row, col+11, Npr_r)
        row += 1
    workbook.close()
    return
```

Code 2.18 Application of cut edge corrosion and writing results to an excel file

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1. Results of External Stability Controls

3.1.1. Sliding Control

The evaluation of sliding resistance for maximum and minimum values of strength I (STR I) type of load combination and capacity demand ratio (CDR) value are presented in Table 3.1.

Table 3.1 Evaluation of sliding resistance

Item	Unit	STR I (Max)	STR I (Min)
Lateral Load, H_m	kN/m	157.55	94.53
Total Vertical Load	kN/m	524.92	381.63
Nominal Sliding	kN/m	354.06	257.41
Factored Sliding, V_f	kN/m	354.06	257.41
Is $V_f > H_m$	-	Yes (safe)	Yes (safe)
Critical Values:			
$V_{f\text{-min}}$	kN/m	271.22	-
$H_{m-\max}$	kN/m	157.55	-
Is $V_{f-\min} > H_{m-\max}$?	-	Yes (safe)	-
CDR = $V_{f-\min}/H_{m-\max}$	-	1.72	-

3.1.2. Eccentricity Limit Check

Eccentricity check is simply the step where the calculations which correspond the conventional turnover evaluation is made. The results of this step is presented in Table 3.2. As it was desired to have a conservative design from any other aspect but pullout, this step is also intended to be adequate in a way that investigation on pullout won’t be disturbed by any other aspect. However, external stability calculations do not concern the pullout behavior in general as the wall acts like any other conventional reinforced concrete retaining wall when it comes to external stability controls.

Table 3.2 Evaluation of eccentricity

Item	Unit	STR I (Max)	STR I (Min)
Total vertical load	kN/m	524.92	381.63
Total resisting moments	kN-m/m	1036.47	742.54
Overturning moments	kN-m/m	322.46	193.48
Net moments	kN-m/m	714.01	549.06
Location of resultant	m	1.36	1.44
Eccentricity	m	0.39	0.31
Limiting Eccentricity	m	0.875	0.875
Is the resultant within limiting eccentricity?	-	Yes(Safe)	Yes(Safe)
Critical values:			
Overturning moment	kN-m/m	322.46	-
Resisting moment	kN-m/m	814.21	-
Net moment	kN-m/m	491.75	-
Vertical load	kN/m	402.1	-
Location of resultant	m	2.02	-
Eccentricity	m	-0.27 (therby, = 0)	-
Limiting eccentricity	m	0.875	-
Is the resultant within limiting eccentricity?	-	Yes(Safe)	-
Effective base width	m	3.5	-

3.1.3. Bearing Capacity Check

Table 3.3 Evaluation of bearing capacity

Item	Unit	STR I (max)	STR I (min)	Service
Effective base width	m	2.72	2.88	2.80
Bearing stress	kN/m^2	192.99	132.51	137.51
Factored bearing resistance	kN/m^2	482.77	420.81	451.79
CDR	-	2.50	3.18	3.29
Critical values:				
Effective base width	m	2.44	-	-
Bearing stress, σ_v	kN/m^2	164.8	-	-
Factored bearing resistance, σ_r	kN/m^2	482.77	-	-
Is $\sigma_v < \sigma_r$	-	Yes (Safe)	-	-
CDR, σ_r / σ_v	-	2.93	-	-

3.2. Results of Internal Stability Controls

3.2.1. Tension Failure Check

Table 3.4 Corrosion calculations for tension failure mode

Item	**Unit**	**Value**
Lose of zinc (first 2 years)	mm/year	0.015
Lose of zinc (subsequent years)	mm/year	0.004
Lifetime of zinc	years	15
Remaning design life	years	60
Lose of steel	mm/year	0.012
Total lose of steel	mm	Oca.44
Remaining cross section	mm^2	128
$T_{allowable}$	kN	181.76
$T_{resistance}$	kN	136.20

Hence, the evaluation of tensile failure resulted as follows:

- For 1. level at 0.8 m from top of wall:

  $T_r = 136.32$ kN > 27.68 kN = T_{max} [SAFE]

- For 2. level at 1.6 m from top of wall:

  $T_r = 136.32$ kN > 27.60 kN = T_{max} [SAFE]

- For 3. level at 2.4 m from top of wall:

  $T_r = 136.32$ kN > 36.31 kN = T_{max} [SAFE]

- For 4. level at 3.2 m from top of wall:

  $T_r = 136.32$ kN > 44.14 kN = T_{max} [SAFE]

- For 5. level at 4.0 m from top of wall:

  $T_r = 136.32$ kN > 51.09 kN = T_{max} [SAFE]

- For 6. level at 4.8 m from top of wall:

  $T_r = 136.32$ kN > 41.44 kN = T_{max} [SAFE]

3.2.2. Pullout Failure Check

The evaluation of pullout failure is based on pullout criteria length and pullout resistance per reinforcement element. Pullout criteria evaluation has resulted as follows:

- For 1. layer from top: L_a = 1.66 m and L_e = 1.84 m [SAFE]

  1.84 > 0.4 m (pullout criteria) and 1 m (L_e min)

- For 2. layer from top: L_a = 1.66 m and L_e = 1.84 m [SAFE]

  1.84 > 0.27 m (pullout criteria) and 1 m (L_e min)

- For 3. layer from top: L_a = 1.56 m and L_e = 1.94 m [SAFE]

  1.94 > 0.29 m (pullout criteria) and 1 m (L_e min)

- For 4. layer from top: L_a = 1.08 m and L_e = 2.42 m [SAFE]

  2.42 > 0.31 m (pullout criteria) and 1 m (L_e min)

- For 5. layer from top: L_a = 0.6 m and L_e = 2.9 m [SAFE]

  2.9 > 0.35 m (pullout criteria) and 1 m (L_e min)

- For 6. layer from top: L_a = 0.12 m and L_e = 3.38 m [SAFE]

  3.38 > 0.29 m (pullout criteria) and 1 m (L_e min)

Next step to be evaluated is pullout resistance per reinforcement element and its evaluation has resulted as follows:

- P_r value for relevant reinforcement level 1 = 3.87 kN

  N_t = 0.2 (strips) < N_p = 7.15 (strips) (Pullout Failure Governs)

  8 strips are needed in this level

- P_r value for relevant reinforcement level 2 = 6.26 kN

  N_t = 0.2 (strips) < N_p = 4.41 (strips) (Pullout Failure Governs)

  5 strips are needed in this level

- P_r value for relevant reinforcement level 3 = 9.08 kN

$N_t = 0.27$ (strips) < $N_p = 4.0$ (strips) (Pullout Failure Governs)

4 strips are needed in this level

- P_r value for relevant reinforcement level 4 = 14.19 kN

  $N_t = 0.32$ (strips) < $N_p = 3.11$ (strips) (Pullout Failure Governs)

  4 strips are needed in this level

- P_r value for relevant reinforcement level 5 = 20.1 kN

  $N_t = 0.37$ (strips) < $N_p = 2.54$ (strips) (Pullout Failure Governs)

  3 strips are needed in this level

- P_r value for relevant reinforcement level 6 = 26.65 kN

  $N_t = 0.3$ (strips) < $N_p = 1.55$ (strips) (Pullout Failure Governs)

  2 strips are needed in this level

3.3. Results of Parametric Investigation

The S_h values with regard to strip element amount which can be applied are shown in Figure 3.1. The strip element number decreases by depth in the baseline case, thereby the convenience for accommodation of larger S_h values within wall width, occurs as less strip amount means large placement area. As a result of this, the ultimate S_h values appeared to only be accommodated by the sixth reinforcement level with 2 strip elements. Figure 3.2, presents the behaviour of R_c values for the presented S_h values. It should be noted that the decrease of R_c results with increase in L_{pcr} requirement as it was presented in Equation 2.34. Therefore, these two figures present an image of the relation between N, S_h and R_c for all reinforcement levels.

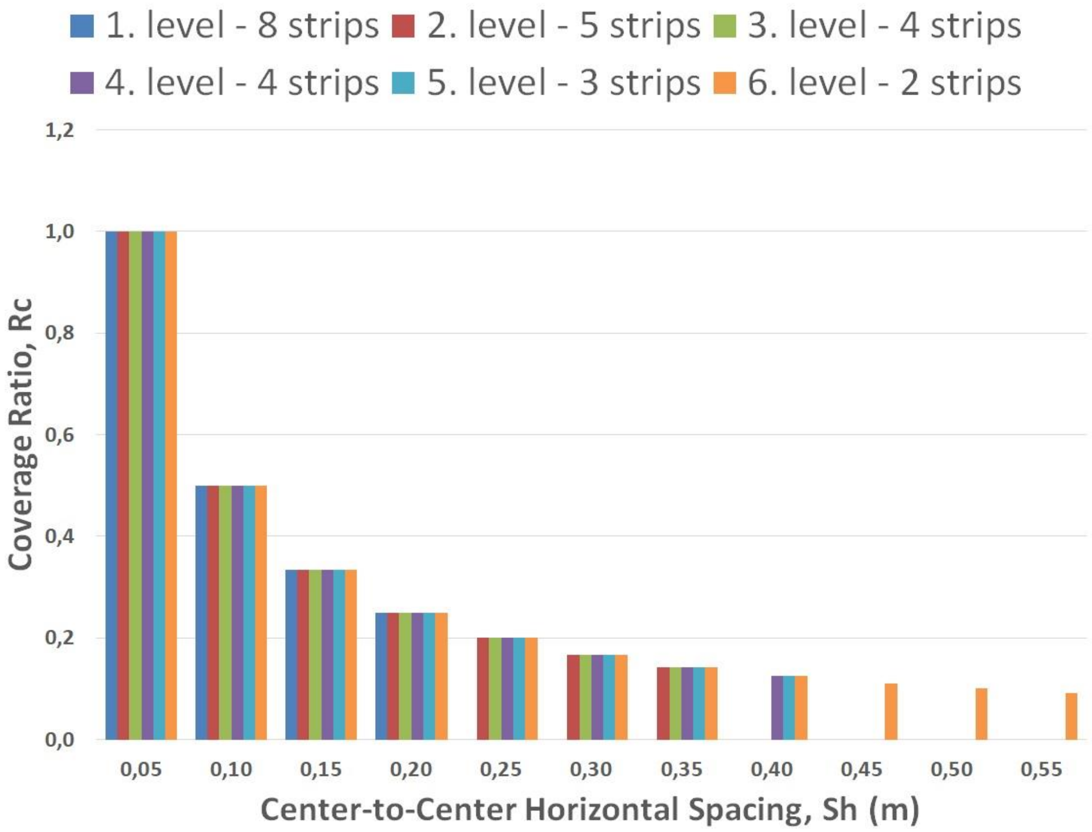

Figure 3.1 Sh tolerations of different amounts of strips within the wall width

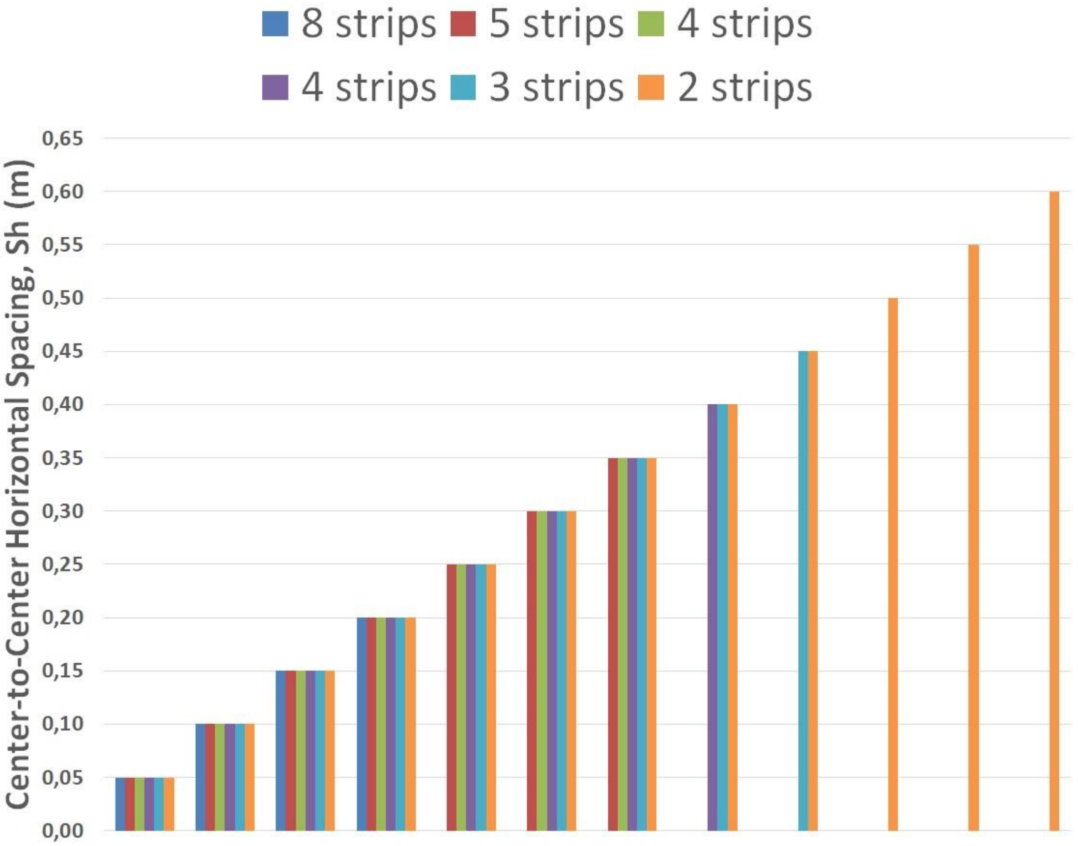

Figure 3.2 Rc – Sh Relation

The increasing L_{pcr} with regard to S_h is shown in Figure 3.3. In first and second reinforcement levels, L_e values are equal since slip surface in the zone shows perpendicularity, which can also be seen in Figure 2.2. The increasing L_{pcr} for all levels tends to have a regular increase by depth starting from second level to fifth level. But, first and sixth levels shows a visible change in their behaviour with regard to other levels. This difference occurs at first level as a result of the fact that Tmax is higher than other levels. This is because of the weight of sloping back and the bigger contributory zone on the top of strips up to wall top. Similarly, sixth level shows a difference in behaviour due to the smaller contributory zone under strips down to wall base, which results with lower T_{max}. Third and fourth levels have same amounts of strip elements, and fifth level has one less than them. Thereby, these three levels present notable outcomes on increasing L_{pcr} per S_h increase and by depth. Figure 3.3, presents that the mentioned increase of L_{pcr} tends to have a gradual nature, which turns the deeper reinforcements out to be more critical with regard to pullout failure. Also, L_e value increase after 2. level, and acts as a compensating aspect for this issue to an extent. However, S_h value is the governing component of design process as it provides to designer a flexibility of decision to establish safer design.

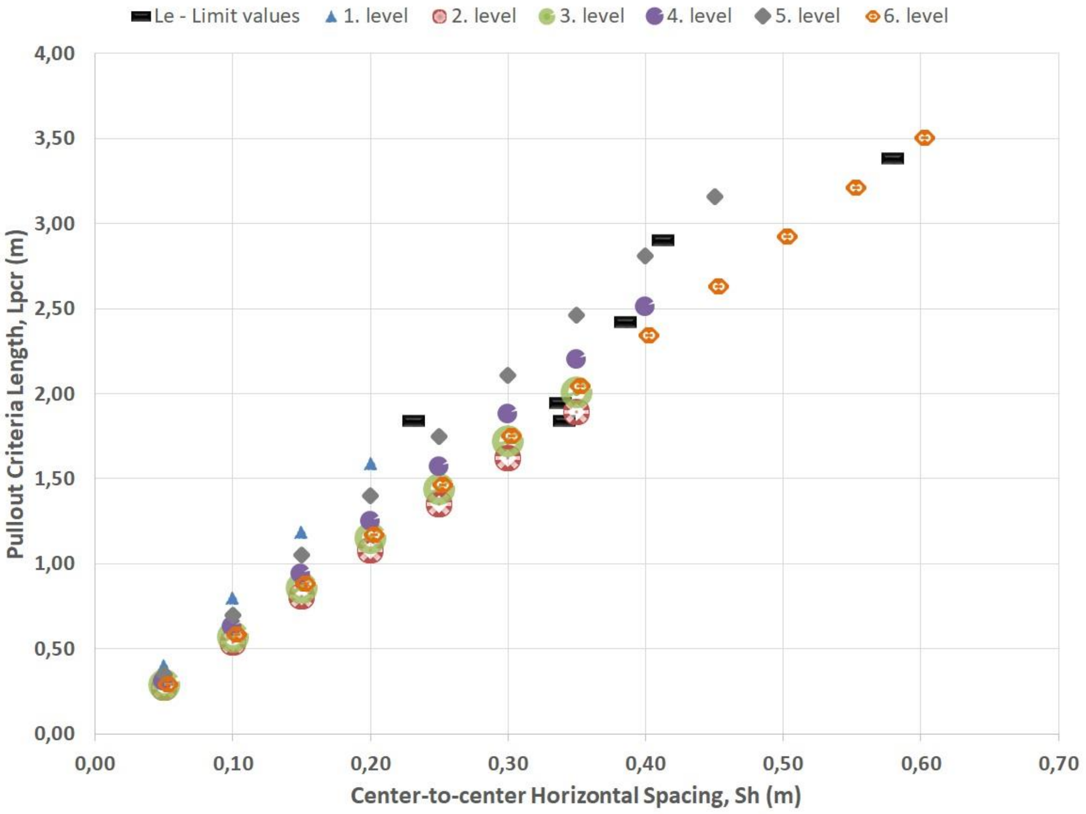

Figure 3.3 L_{pcr} - S_h relation at design stage

3.3.1. Pullout after Cut Edge Corrosion

The Figure 3.4 presents the percentage changes of each reinforcement element. The graph fluctuation results from difference of reinforcement amount and variator effects of T_{max}, F^* and σ_v parameters of Equation 2.35. However, the Figure 3.4 provides a vision of the cut edge corrosion effect which results with an increase for L_{pcr}. The percentage changes those are shown in Figure 3.4 are significant since it is visible that different reinforcement levels resulted with irregularity in the graph. Yet, obviously the change ratios are fluctuating mostly between 6-7 percentages and this range of change is enough to cause hazard as it can be observed in following graphs and results. To present a better understanding for this phenomena's critical effect, comparison of L_{pcr} values for design stage and end of the design life time of structure and L_e limit values are shown in Figure 3.5. Note that, the most critical S_h values are concerned herein. The ultimate S_h values are applied with selecting greatest b multiple before the non-applicable one which makes the L_{pcr} exceed the L_e. Thereby, the vulnerability for some levels that the related L_{pcr} value exceeds its L_e limit is demonstrated in the Figure 3.5.

The following findings are showing that the cut edge corrosion as an ignored factor by American Association of State Highway and Transportation Officials (AASHTO, 2010) and Federal Highway Administration (Elias et al., 2001), is indeed a parameter to be concerned when the usage of the most critical center-to-center horizontal spacing is present. Although design engineers could feel comfortable with choosing the most critical center-to-center horizontal spacing values in their design, it is observed that the failure could be triggered in some of the reinforcement levels due to this design decision.

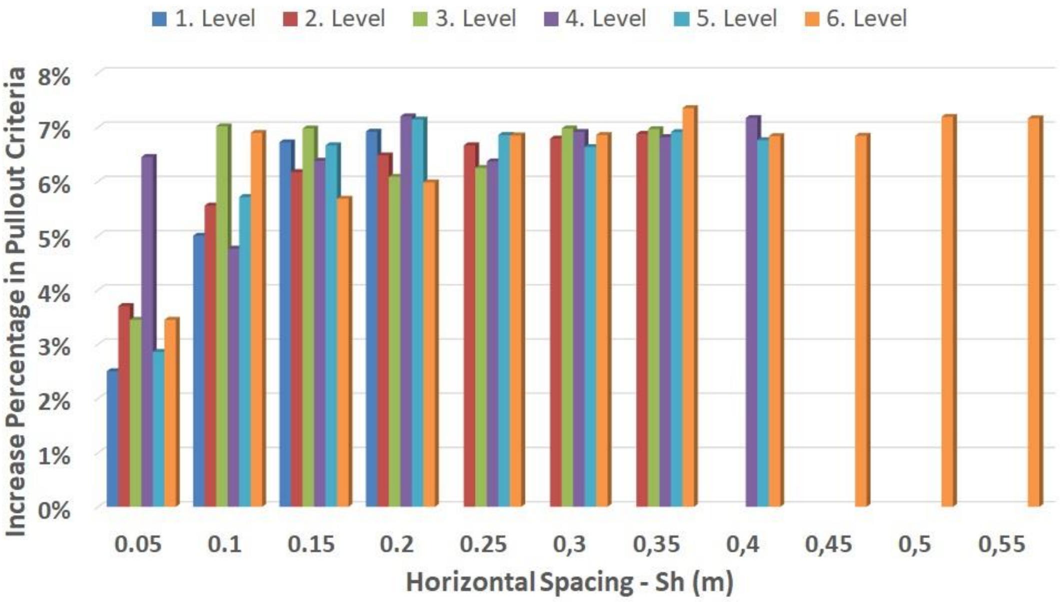

Figure 3.4 Percentage change in L_{pcr} due to cut edge corrosion

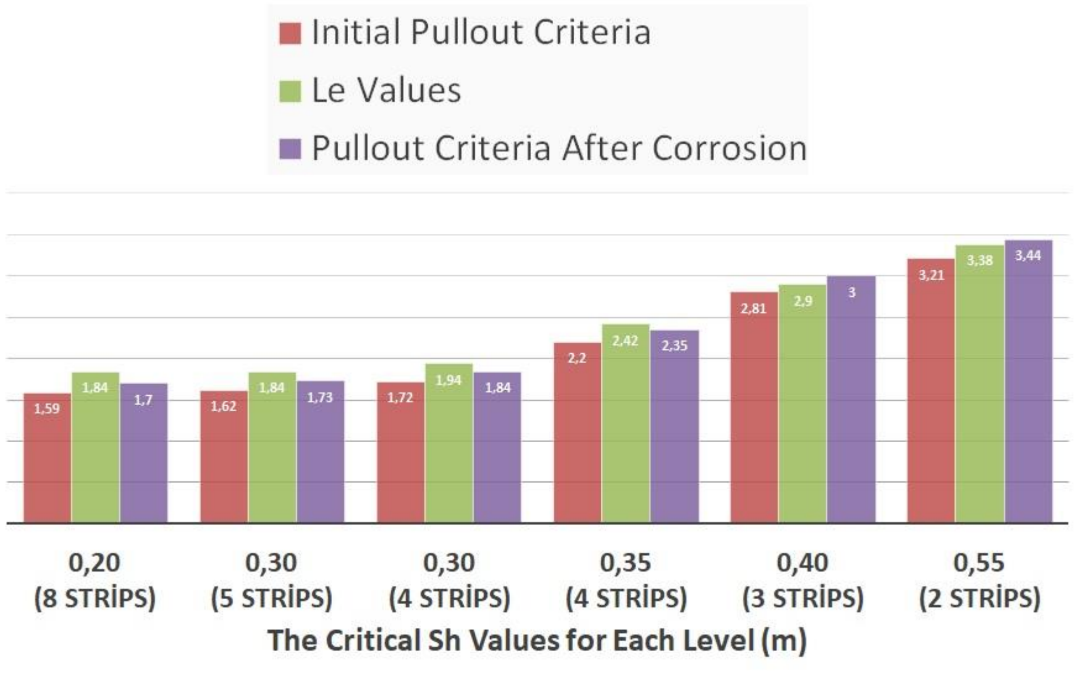

Figure 3.5 L_{pcr} change over design life with regard to critical S_h values

P_{res} with regard to L_e is shown in Figure 3.6, which presents a gradual decrease behaviour by depth. Thus, the pullout failure possibility increase with depth, as the increase of the pullout failure possibility by going deeper within wall, for corroded state of L_{pcr}. P_{res} is one of the two main components of pullout check as Equation 2.37

suggests. Figure 3.7 shows the decimals with and without corrosion effect and their rounded up values, to present the potential required amount change for reinforcement amount. Third level alone is seen to be require one more reinforcement element. This phenomena outcomes as a result of round up of decimal digits for required strip element amount. For example, N_i and N_f of third level are 4.00 and 4.15, respectively, however N_i and N_f of fourth level are obtained as 3.11 and 3.23. This resulted with 5 required strip elements for third level for post-corrosion state while there was no change for the required reinforcement amount for fourth level. First instance shows a critical situation and second suggests that the pre-determined amount is adequate.

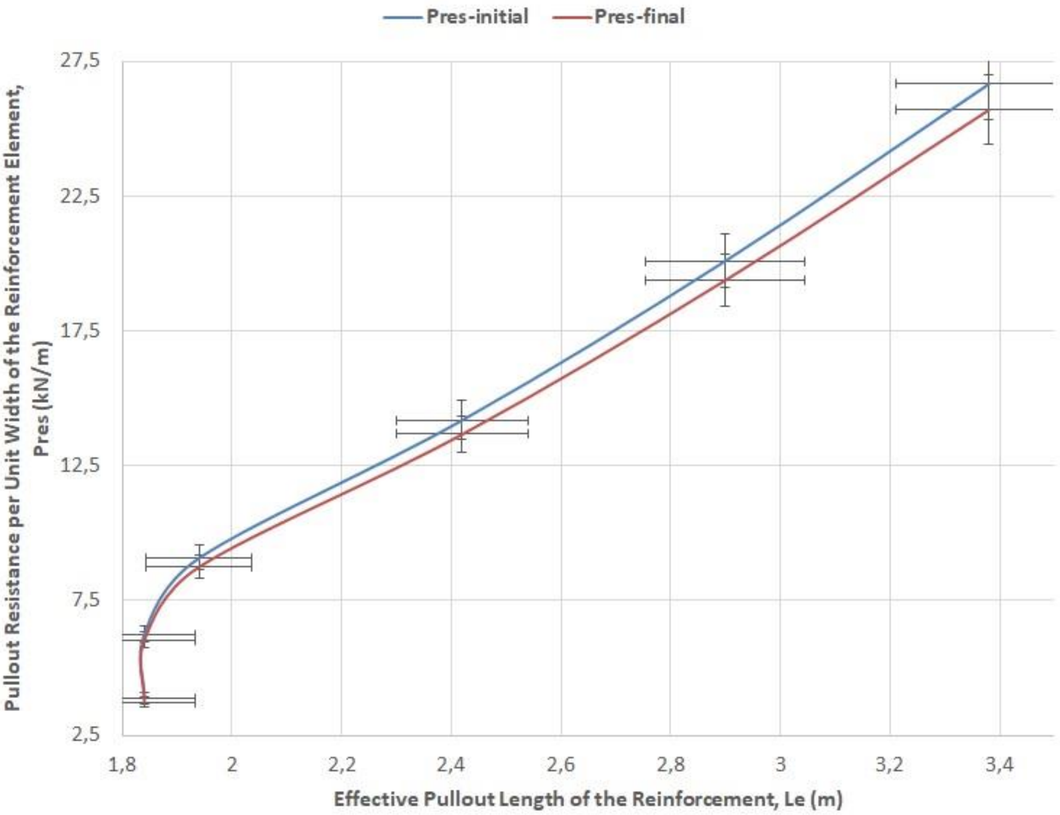

Figure 3.6 P_{res} - L_e relation

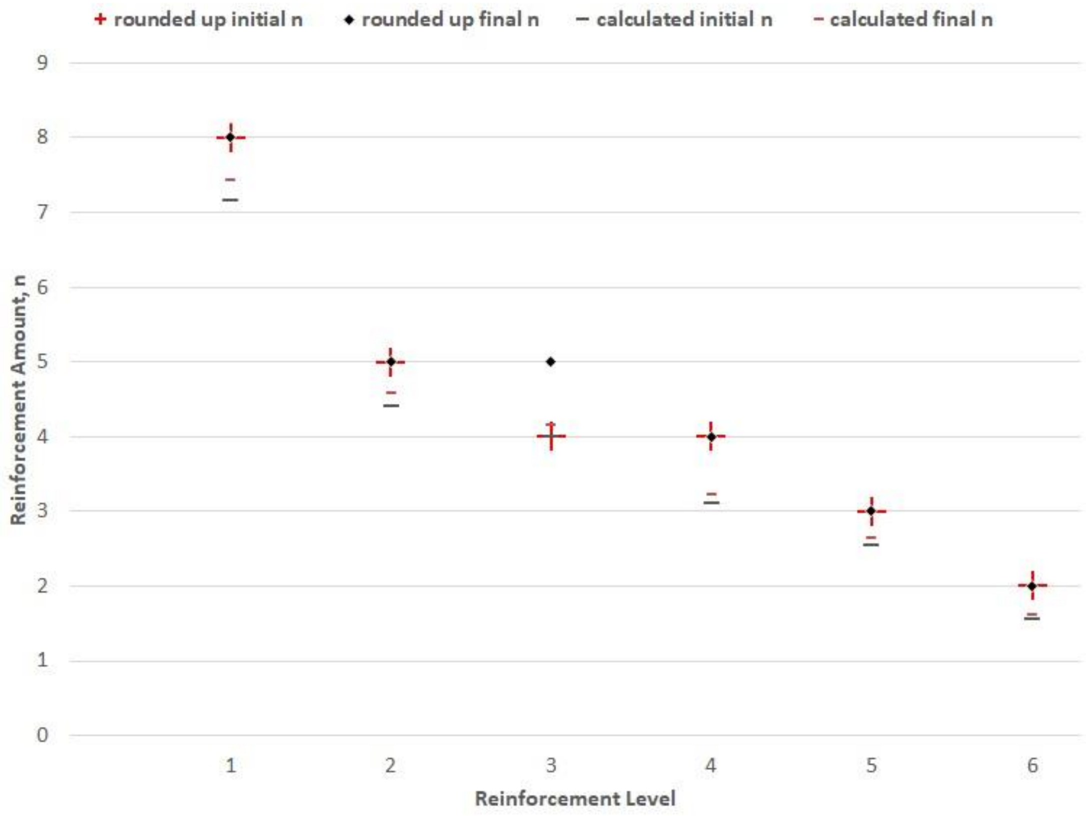

Figure 3.7 Change in required amount of strips as a result of P_{res} decrease

3.4. Discussions

All the calculation steps of external stability analysis have been conducted on the base of relevant specification (AASHTO, 2010) and resulted in a conservative form as it was desired. It should be noted that, as Kim and Salgado suggested, LRFD approach does not requires any additional factor of safety application as it already applies factors within calculation stage (Kim and Salgado, 2012).

All the calculation steps of internal stability analysis have been conducted on the base of relevant specification (AASHTO, 2010) and resulted in a conservative form as it was desired. In order to obtain a conservative design from all the aspects but pullout, Federal Highway Administration's guidelines and American Association of State Highway and Transportation Officials' suggestions on parameters in the absence of experimental data are used (AASHTO, 2010; Elias et al., 2001). It is observed that the conservation suggestions of the specifications aforementioned resulted adequate in a way that parametric study was able to be conducted on pullout without any concern on other stability components.

The external stability and tension failure mode of internal stability calculations are desired to be safe for having a better form for pullout failure mode investigations. The corrosion effect only concerns the tension failure mode according to used specification (AASHTO, 2010). But results has shown that it should also be concerned about pullout failure mode as it can result with failure in some reinforcement levels when the most critical center-to-center horizontal spacing values are used. This is particularly important as design engineers could consider the center-to-center horizontal spacing values safe at the design stage without foreseeing the possible failure, when (AASHTO, 2010) alone is taken into consideration.

”Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes” by Federal Highway Administration suggests that galvanized coupons should be buried in backfill soil and should be checked periodically to monitor the corrosion condition of steel strips, and also it suggests that cut edges of coupons should have a zinc bath in order to be galvanized (Elias et al., 2009). However herein, the investigation is made with the concern of not galvanized cut edges which occurs in absence of galvanization or occurs in case of the immediate loss of galvanization by construction impact damages.

It is observed that both pullout criteria length and the required amount of reinforcement element with regard to pullout mode, are possible to be crucial in case of usage of the most critical center-to-center horizontal spacing between reinforcement strips. These findings could possibly push design engineers to question usage of critical values of center-to-center horizontal spacing values although they seem adequate at the design stage according to The American Association of State Highway and Transportation Officials (AASHTO, 2010).

CHAPTER 4

CONCLUSIONS

A baseline case is designed and a parametric study has been conducted on it in order to investigate the pullout behaviour of MSE wall with steel strip reinforcement type. Pullout criteria length and pullout resistance per unit width of reinforcement element, were two main subjects to be investigated. Incrementally changed reinforcement placement and cut edge corrosion effect to aforementioned parameters were observed and following conclusions are drawn:

- As a matter of course, tolerable center-to-center horizontal spacing values increase with the usage of lesser amount of strip elements, and the pullout criteria length which should definitely be exceeded increases with the increase of center-to-center horizontal spacing between strip elements. Hence, it is observed that lesser amount of strip reinforcement results with greater pullout criteria length values, which is an important aspect to be considered by design engineers when it comes to obtaining an optimum amount of reinforcement element per reinforcement level.
- The gradual increase of the pullout criteria length with regard to increasing center-to-center horizontal spacing between reinforcement elements indicates the fact that the pullout criteria length becomes gradually crucial with depth. Therefore, relatively larger center-to-center spacing decisions should be avoided.
- Cut edge corrosion appeared to have a notable effect on pullout criteria length, since it has been observed that deeper reinforcement levels with lesser reinforcement amount, are tend to be exceeded by the effect of cut edge corrosion. Therefore, design engineers should consider this possibility in presence of ungalvanized cut edges, although this particular phenomena is neglected by the specification which has been used.
- Cut edge corrosion has also results with a decrease in pullout resistance per unit width of reinforcement element in a way that this phenomena has a gradually decreasing nature by depth. This makes upper reinforcement levels more critical as they have greater changes with regard to deeper ones. It is observed that required amount of reinforcement element in a particular reinforcement level might not be

adequate once cut edge corrosion process is done, and this incident also takes place as a result of the mentioned decrease of pullout resistance per unit width of reinforcement element. It should be noted this incident comes into reality when the most critical center-to-center spacing values are chosen for reinforcement replacement. This conclusion becomes significant as the design engineers could not see any problem with choosing the most critical center-to-center spacing values (as it may require less reinforcement, thus it may be cost-friendly) at the design stage with not taking cut edge corrosion into consideration. Therefore, design engineers should avoid using the critical center-to-center spacing values in order not to encounter such an incident.

To avoid possible dangers above, extending the reinforcement length, thus effective length works adequately enough. However, same goal could be achieved by avoiding the preference of the most critical center-to-center spacing as well. It should be noted that all these conclusions might help the design engineers to broaden their vision about the effect of coverage ratio and its components to the mechanically stabilized earth wall to be designed. Nevertheless, it should be noted that the study has been conducted with regard to AASHTO (AASHTO, 2010) and validating the presented conclusions by a large scale test or numerical investigation could provide a better view on the topic.

REFERENCES

AASHTO. LRFD Bridge Design Specification. Technical report, Washington, D.C.: American Association of State Highway and Transportation Officials, 2010.

T. Allen, B. Christopher, V. Elias, and J. DeMaggio. Development of the simplified method for internal stability design of mechanically stabilized earth walls. Technical report, Citeseer, 2001.

R. J. Bathurst, Y. Miyata, and T. M. Allen. Deterministic and probabilistic assessment of margins of safety for internal stability of as-built pet strap reinforced soil walls. Geotextiles and Geomembranes, 48(6):780–792, 2020.

R. R. Berg, B. R. Christopher, and N. C. Samtani. Design of mechanically stabilized earth walls and reinforced soil slopes. FHWA, Washington, DC, Report No. FHWANHI-10-024, 2009a.

R. R. Berg, B. R. Christopher, and N. C. Samtani. Design of mechanically stabilized earth walls and reinforced soil slopes. FHWA, Washington, DC, Report No. FHWANHI-10-025, 2009b.

R. Bligh, J. Briaud, K. Kim, and A. Abu-Odeh. Design of roadside barrier systems placed on mse retaining walls (nchrp report 663). Washington, DC: Transportation Research Board, 2010.

E. Bourgeois, A. Corfdir, and T.-L. Chau. Analysis of long-term deformations of mse walls based on various corrosion scenarios. Soils and foundations, 53(2): 259–271, 2013.

B. A. Castellanos. Internal design of Mechanically Stabilized Earth (MSE) retaining walls using crimped bars. Utah State University, 2010.

T. Chalermyanont and C. H. Benson. Reliability-based design for internal stability of mechanically stabilized earth walls. Journal of Geotechnical and Geoenvironmental Engineering, 130(2):163–173, 2004.

T. Chalermyanont and C. H. Benson. Reliability-based design for external stability of mechanically stabilized earth walls. International Journal of Geomechanics, 5(3):196–205, 2005.

B. R. Christopher, V. Elias, et al. Mechanically stabilized earth walls and reinforced soil slopes design and construction guidelines. Technical report, United States. Federal Highway Administration, 1997.

M. Drusa, J. Vlˇcek, M. Holiˇckov´a, and L. Kais. Analytical and numerical evaluation of limit states of mse wall structure. Civil And Environmental Engineering Reports, 12(2):145–152, 2016.

V. Elias, B. R. Christopher, R. R. Berg, R. R. Berg, et al. Mechanically stabilized earth walls and reinforced soil slopes: design and construction guidelines (updated version). Technical report, United States. Federal Highway Administration, 2001.

V. Elias, K. Fishman, and R. Berg. Corrosion/degradation of soil reinforcements for mechanically stabilized earth walls and reinforced soil slopes, publication no: Fhwa-nhi-09-087. Technical report, US Department of Transportation, 2009.

D. Hartman, M. Ledezma, M. Xiao, and M. Zoghi. Shake table test of mse wall with tire derived aggregates (tda) backfill. In Geo-Congress 2013: Stability and Performance of Slopes and Embankments III, pages 1168–1177, 2013.

K. Hatami and A. Witthoeft. A numerical study on the use of geofoam to increase the external stability of reinforced soil walls. Geosynthetics International, 15 (6):452–470, 2008.

B. Hu and Z. Luo. Life-cycle reliability-based assessment of internal stability for mechanically stabilized earth walls in a heavy haul railway. Computers and Geotechnics, 101:141–148, 2018.

D. Kim and R. Salgado. Load and resistance factors for external stability checks of mechanically stabilized earth walls. Journal of Geotechnical and Geoenvironmental Engineering, 138(3):241–251, 2012.

T. Kim, S.-Y. Lee, M. S. Nam, and H. Han. Pullout behavior of mechanically stabilized earth wall abutment by steel reinforcement and backfill properties. Journal of the Korea Academia-Industrial cooperation Society, 19(11):750–757, 2018.

H. Liu. An analytical method for reinforcement load of wrapped-face mse walls before full mobilization of soil strength. In Geo-Congress 2013: Stability and Performance of Slopes and Embankments III, pages 519–528, 2013.

R. L. Parsons, J. Han, C. Breckwoldt, et al. Investigation of variations in corrosion potential in mechanically stabilized earth backfill due to migration of fines. Technical report, University of Kansas. Dept. of Civil, Environmental and Architectural, 2019.

R. L. Parsons, Z. A. Brady, T. N. Walkenbach, J. Han, S. Kulesza, and J. Brennan. Resistivity measurement of backfill for mechanically stabilized earth walls. Journal of Materials in Civil Engineering, 32(3):04019367, 2020.

F. Reinforced Earth. Reinforced earth İnşaat proje ve ticaret A.Ş.. http://www.reinforcedearth.com.tr/services-reinforced.html , 2019.

M. R. Sadat, J. Huang, S. Bin-Shafique, and S. Rezaeimalek. Study of the behavior of mechanically stabilized earth (mse) walls subjected to differential settlements. Geotextiles and Geomembranes, 46(1):77–90, 2018.

R. V. Siddharthan, V. Ganeshwara, B. L. Kutter, M. El-Desouky, and R. V. Whitman. Seismic deformation of bar mat mechanically stabilized earth walls. i: Centrifuge tests. Journal of geotechnical and geoenvironmental engineering, 130(1):14–25, 2004a.

R. V. Siddharthan, V. Ganeshwara, B. L. Kutter, M. El-Desouky, and R. V. Whitman. Seismic deformation of bar mat mechanically stabilized earth walls. ii: A multiblock model. Journal of geotechnical and geoenvironmental engineering, 130(1):26–35, 2004b.

A. Srivastava and V. B. Chauhan. Numerical studies on two-tiered mse walls under seismic loading. SN Applied Sciences, 2(10):1–7, 2020.

M. Tajabadipour, M. Dehghani, B. Kalantari, and S. Lajevardi. Laboratory pullout investigation for evaluate feasibility use of scrap tire as reinforcement element in mechanically stabilized earth walls. Journal of Cleaner Production, 237:117726, 2019.

A. Thapalia, D. M. Borrok, S. Nazarian, and J. Garibay. Assessment of corrosion potential of coarse backfill aggregates for mechanically stabilized earth walls. Transportation research record, 2253(1):63–72, 2011.

J. Thornley and R. Siddharthan. Effects of corrosion aggressiveness on mse wall stability in Nevada. In Earth Retention Conference 3, pages 539–547, 2010.

T. Vahab and P. Helda. Probabilistic-based analysis of mse walls using the Latin hypercube sampling method. American Society of Civil Engineers, 2018.

F. Wall System. Beautifully built wall. https://www.flexmse.com/photo-gallery/, 2021.

R. M. Walthall, J. Wang, P. Kiousis, and A. Khan. Finite-element analyses of mechanically stabilized earth walls subjected to midlevel seismic loads. Journal of performance of constructed facilities, 27(2):171–180, 2013.

Y. Wang and M. Wang. Internal stability of reinforced soil retaining structures with cohesive backfills. Transportation research record, (1414), 1992.

J. Wartman, E. A. Rondinel-Oviedo, and A. Rodriguez-Marek. Performance and analyses of mechanically stabilized earth walls in the tecoman, Mexico earthquake. Journal of performance of constructed facilities, 20(3):287–299, 2006.

M. T. Weldu, J. Han, S. M. Rahmaninezhad, R. L. Parsons, J. I. Kakrasul, et al. Pullout resistance of mechanically stabilized earth wall steel strip reinforcement in uniform aggregate. Technical report, University of Kansas. Dept. of Civil, Environmental, and Architectural, 2015.

I. E. Zevgolis and P. L. Bourdeau. Probabilistic analysis of the external stability of mse structures using Monte Carlo simulations. In 12th International Conference of International Association for Computer Methods and Advances in Geotechnics (IACMAC), pages 1804–1810. Citeseer, 2008a.

I. E. Zevgolis and P. L. Bourdeau. Stochastic modeling of redundancy in mechanically stabilized earth (mse) walls. In GeoCongress 2008: Geosustainability and Geohazard Mitigation, pages 1179–1186. 2008b.