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Finite element analysis of external earth pressure on reinforced soil wall in front of soil nail wall

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ABSTRACT

Motorway widening has been increasingly required to relieve traffic congestion in urban areas. This often involves placement of a new retaining wall (e.g. a reinforced soil wall (RSW)) adjacent to an existing battered embankment with excavation temporarily supported, e.g. by a temporary soil nail wall (SNW). Often due to space constraint, a narrow RSW is constructed in front of the SNW. Modelling the interaction of the SNW and the RSW and considering the magnitude of the lateral earth pressure on the back of the RSW could pose a challenge to the retaining wall designer. This paper uses finite element method to investigate the interaction between the SNW and RSW, especially to investigate the earth pressure acting on the back of the RSW due to the interaction.

Keywords: retaining wall, interaction, lateral earth pressure, finite element method

1 INTRODUCTION

Motorway widening or upgrade projects often require to cut into the existing battered embankment, and temporarily support the cut with a SNW and build a RSW in front of the temporary SNW to accommodate an additional lane on top of the RSW and a service road in front of the RSW (Figure 1). The SNW may be designed as a long-term permanent retaining structure to meet all the relevant geotechnical design requirements. In between the face of the SNW and the back of the RSW, the gap is often backfilled with drainage fill material.

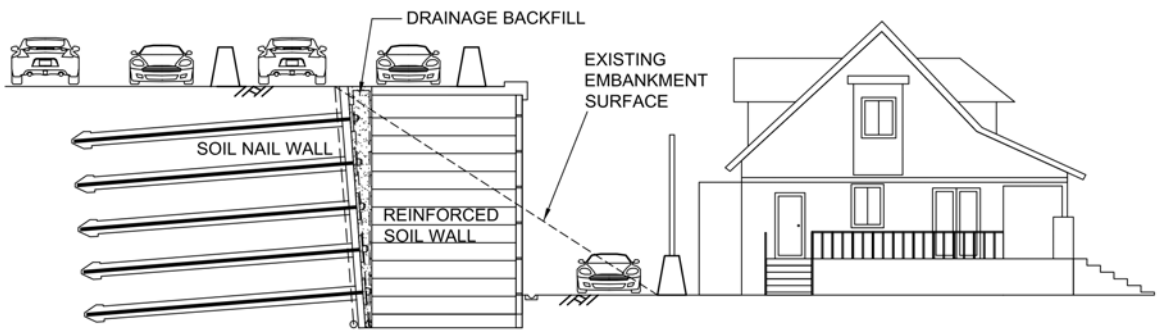

Figure 1. A narrow RSW constructed within limited space

This retaining system consists of three elements: the buried SNW, the narrow RSW and a thin drainage backfill wedge in between.

To the best knowledge of the authors of this article, the retaining system and particularly the lateral earth pressure on the back of the RSW are not comprehensively investigated in current literature. Adopting an active earth pressure on the back of the RSW could be overly conservative and result in uneconomical design. On the other hand, the horizontal force acting on the back of the RSW might be ignored by some designers considering the following factors:

- The SNW is designed to meet long-term stability and considered as a self-supported structure without transferring any earth pressure
- The drainage backfill is relatively small with a close to vertical soil nail face and any earth pressure due to this small wedge is likely to be negligible

In this case, the external design of the RSW just requires to check bearing capacity. However, ignoring the interaction between the SNW and the RSW and hence the horizontal force acting on the back of the RSW may reduce the bearing factor of safety, and potentially cause sliding and overturning failures of the RSW.

Some standards require a minimum width of a RSW, e.g. ≥ 0.7Hm (BS8006 and GEOGUIDE06) or 0.6H+1m (RMS R57) for conventional reinforced soil walls. As far as the authors know little research has been done in this area to guide how geotechnical engineers should quantify the driving force acting on the back of the RSW and no design guidelines are available to mitigate the potential risks of failures due to the interaction. This study is the first as far as the authors know to investigate the interaction between the SNW and the RSW and pressure transferred through this retaining system.

2 FINITE ELEMENT METHOD (FEM)

2.1 Model Details

A finite element program PLAXIS 2D Version 2012 is used to study the interaction between the SNW and RSW. The SNW is installed to support the excavation of the existing embankment. When the deformation of the SNW is completed, the RSW is constructed in front with a thin layer of drainage backfill between the face of the SNW and the back of the RSW. Staged construction is simulated in the FEM modelling with the soil nails to be installed row by row during excavation of the existing embankment, top down, and the RSW to be constructed layer by layer, bottom up.

The following assumptions are adopted in the FEM:

- The RSW is constructed only after the deformation of the SNW is completed.
- The RSW is simplified as a rigid body with high elastic modulus (1000MPa).
- Compaction stress induced during construction is not considered.
- Traffic load of 20kPa is applied on top of the retaining system.

An example of this retaining system based on a motorway upgrade project is studied using the FEM. The retaining structure details are given in Table 1.

Table 1: Wall details

Wall	Height (m)	Width (m)	Nail Details			
			Horizontal & Vertical Spacing (m)	Length (m)	Hole Diameters (m)	No. of Rows
SNW	6.5	-	1	10	0.15	7
RSW	6.5	4.9[1]	-	-	-	-

[1] Width of RSW is equal to 0.6H+1, based on RMS R57

Two soil constitutive models, namely Mohr-Coulomb (MC) and Hardening Soil (HS) models, are used in the FEM and the results are compared. Different elastic moduli of the foundation material ranging from 10MPa to 1000MPa are examined for a parametric study. Design parameters used in the FEM are shown in Table 2 and Table 3.

Table 2: Material design parameters

Material	Material Model	Behaviour Type	γ (kN/m^3)	c' (kPa)	ϕ' (°)	E' (MPa)	E_{50}^{ref} & E_{ode}^{ref} (MPa)	E_{ur}^{ref} (MPa)
Foundation	MC	Drained	19	4	28	10 – 1000	-	-
	HS	Drained	19	4	28	10 – 1000	10 – 1000	30 – 3000
Embankment	MC	Drained	19	4	26	10	-	-
	HS	Drained	19	4	26	10	10	30
Drainage Backfill	MC	Drained	20	5	30	40	-	-
	HS	Drained	20	5	30	40	40	120
RSW	Elastic	Drained	23	-	-	1000	-	-

Table 3: Structural element parameters

Material	Modelling	E' (GPa)	Thickness (mm)	Inclination (°)	EA (kN/m)	EI (kNm^2/m)
Nail	Geo-grid	20	-	15	3.5x10^5	-
Shotcrete	Plate	20	200	-	4x10^6	1.3x10^4

The PLAXIS model is shown in Figure 2.

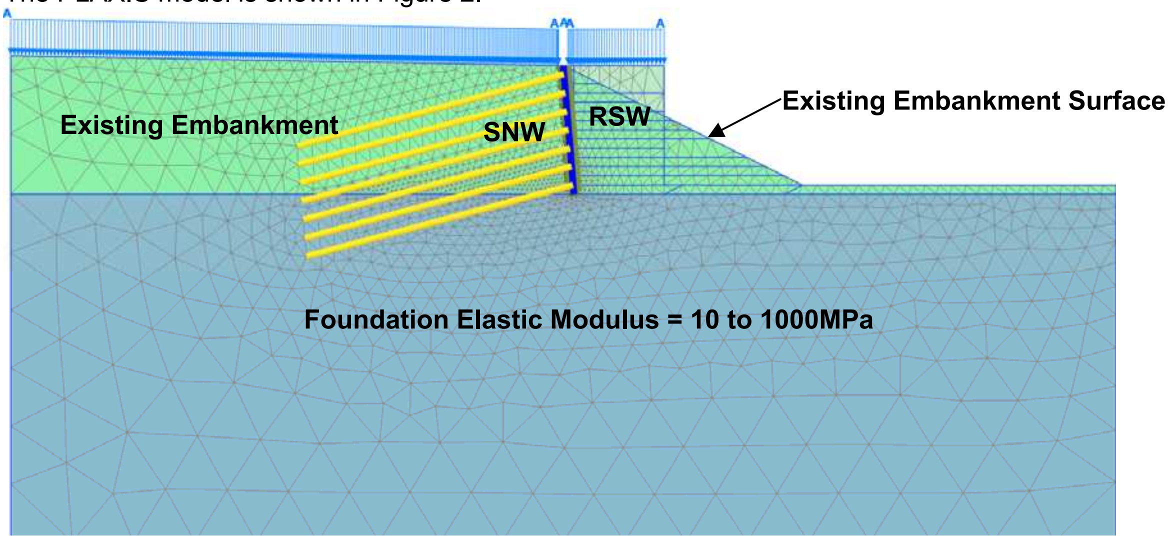

Figure 2. PLAXIS model analysis

2.2 Verifying the FEM against Rankine's active earth pressure theory

The PLAXIS model in Figure 2 is modified by removing the SNW and drainage backfill and having existing embankment material up to the back of the RSW as a conventional RSW. According to Rankine's earth pressure theory, active driving force is equal to 177kN at the back of the 6.5m high RSW assuming the following embankment material parameters: γ = 19kN/m^3, c' = 4kPa and ϕ' = 26° as given in Table 2. The active equivalent force resulted from PLAXIS is 184.6kN which agrees well with the result from Rankine's theory. The above process indirectly demonstrates that the finite element model could be used to study the pressure acting on the back of the RSW.

3 ANALYSIS RESULTS AND DISCUSSION

3.1 Settlement and deformation of the retaining walls

In the FEM, it is assumed that the RSW starts to be constructed only after the deformation of the SNW is completed. As the RSW is being placed, the ground beneath the RSW will start to settle. The magnitude of the ground settlement is related to the elastic modulus of the foundation material. Figure 3 shows the relationship between the maximum settlement and foundation elastic modulus.

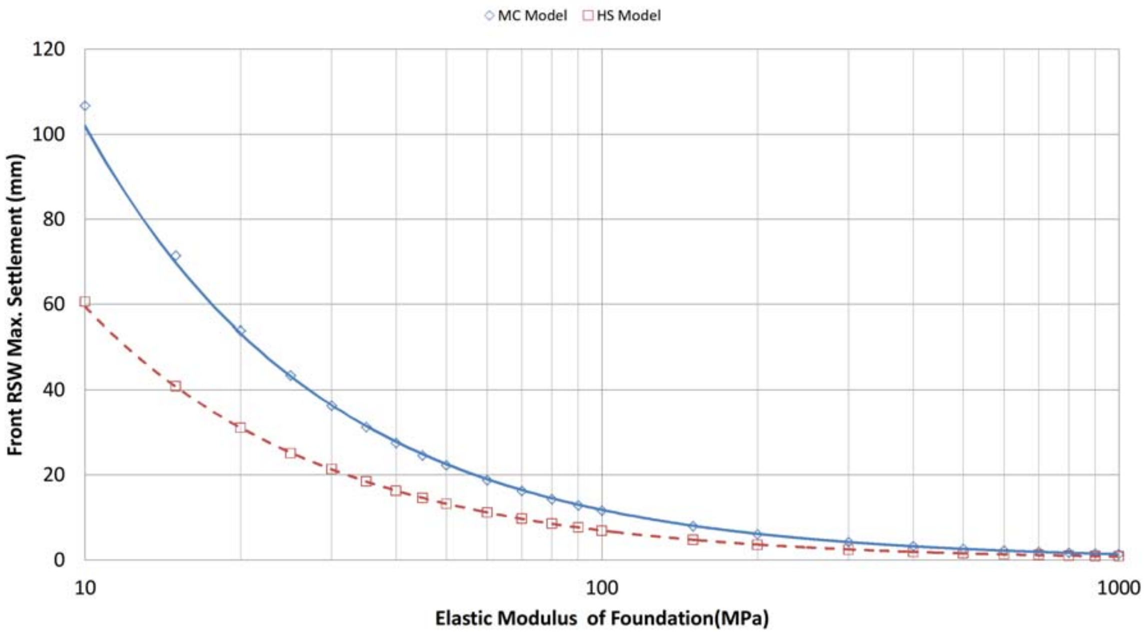

Figure 3. Front RSW settlement against various elastic moduli of foundation

The graph indicates the settlement increases rapidly when elastic modulus of foundation material is less than 40MPa. In addition, the settlement predicted using MC model is approximately 70% higher than those using from HS model. The difference becomes insignificant once the elastic modulus becomes larger and settlement is smaller. This indicates HS model is preferred for weak foundation material as it tends to avoid overestimation of the settlement.

While the foundation underneath the RSW settles, the surrounding soil is also dragged down and settles, which causes the SNW to deform and tilt toward the RSW (Figure 4).

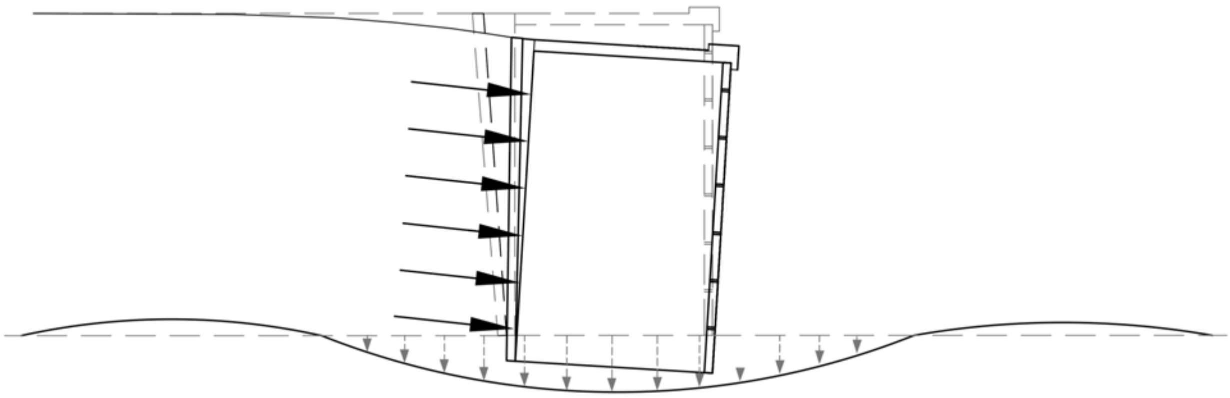

Figure 4. RSW settlement causes deformation of SNW behind

The deflection of the SNW using MC and HS models with different elastic moduli of the foundation are plotted in Figures 5 and 6 respectively.

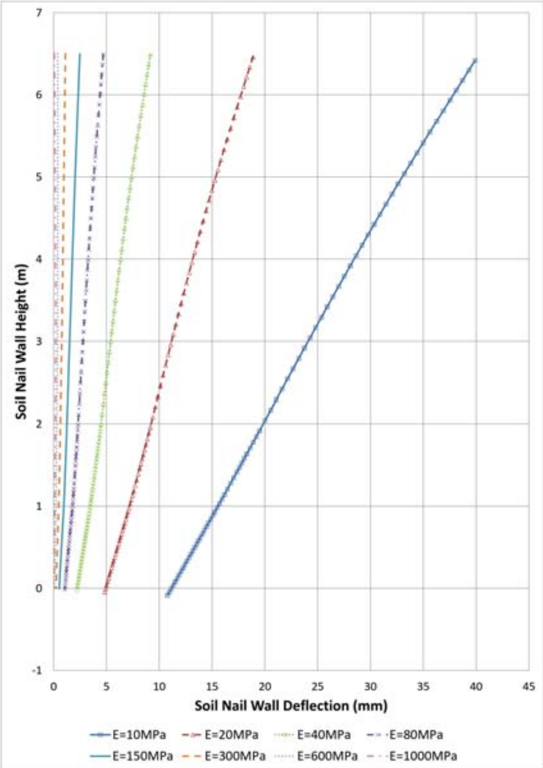

Figure 5. SNW deflection using MC Model

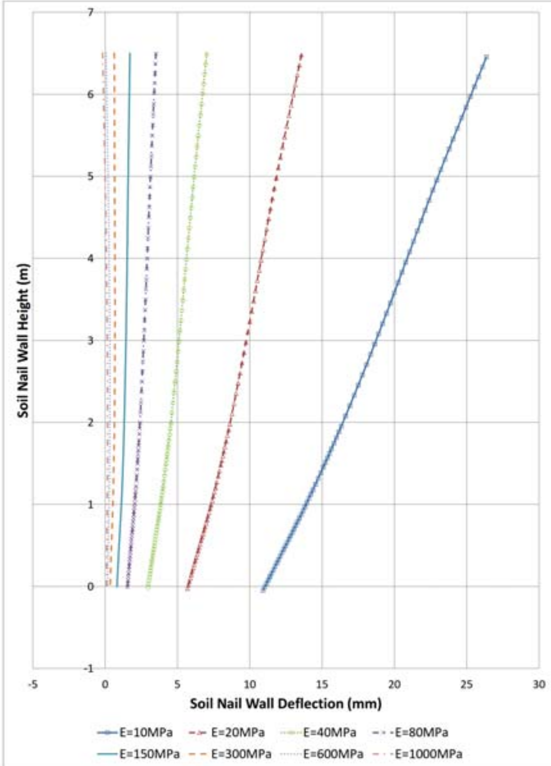

Figure 6. SNW deflection using HS Model

Figure 5 shows the maximum deflections of the SNW range from 0 to 40mm using MC model and Figure 6 shows the maximum deflections of the SNW range from 0 to 27mm using HS model. Again MC model tends to give a larger deformation compared to the HS model.

3.2 Pressure induced by SNW deflection

The settlement of the RSW due to its self-weight will induce the deflection of the face of the SNW. The forward movement of the SNW will push the drainage backfill in between the SNW and the back of the RSW and create a driving horizontal earth pressure acting on the back of the RSW. A cross section is vertically cut along the back of the RSW and an equivalent driving force of this pressure can be obtained from the PLAXIS analysis results. This equivalent force is plotted against the maximum RSW settlement and the maximum SNW deflection to investigate the relationship between deformation and the driving force, as shown in Figure 7 and 8 respectively.

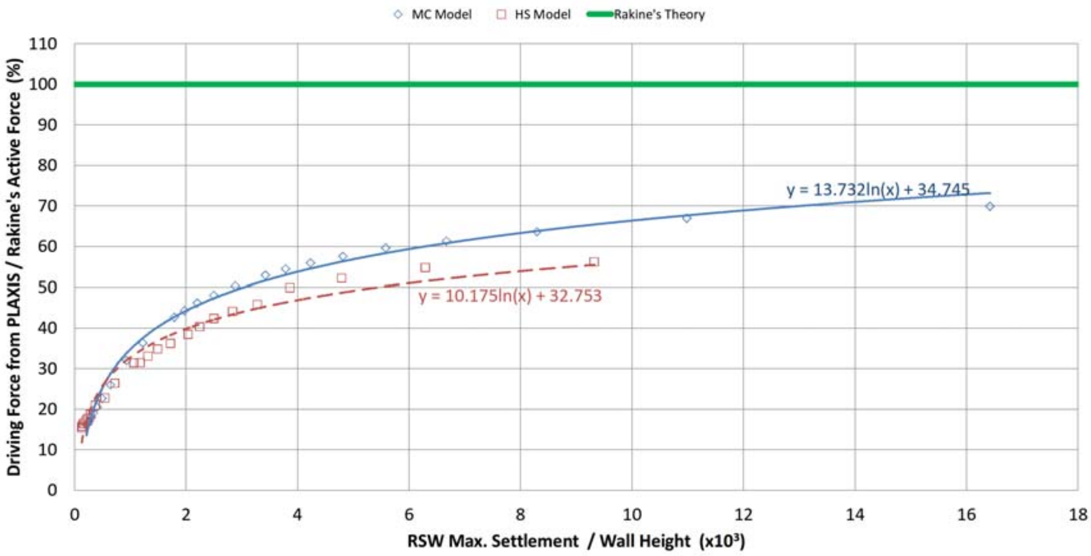

Figure 7. Driving force ratio (equivalent driving force from the PLAXIS analysis / the Rankine's active force) against the RSW settlement ratio (RSW max. settlement / wall height)

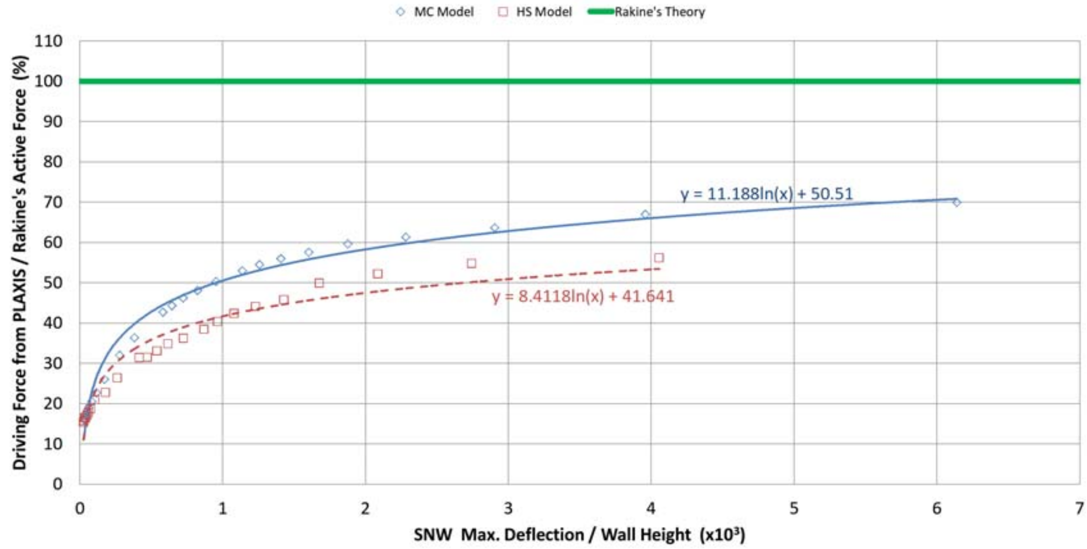

Figure 8. Driving force ratio against the SNW deflection ratio (SNW max. deflection / wall height)

It is noted that the Rankine's active force is 177kN (refer to Section 2.2) and wall height is 6.5m. It is found the driving force ratio at the back of the RSW ranges from 15% to 70%, and is dependent on the magnitude of the RSW settlement and the SNW deflection.

The driving force calculated from both the MC and HS models shows a good agreement. The driving force becomes greater when the settlement of the RSW or the deflection of the SNW is larger and the relationship is non-linear. The driving force ratio increases rapidly from 15% to 45% when the RSW settlement ratio increases from $0.1x10^{-3}$ to $2.5x10^{-3}$, or when the SNW deflection ratio increases from $0.1x10^{-3}$ to $1x10^{-3}$. When the settlement or deflection increases further, the driving force ratio gradually increases to its maximum of 70%.

The figures indicate a small settlement of the RSW or deflection of the SNW can lead to a significant driving force at the back of the RSW. By ignoring the interaction of the RSW and the SNW and hence ignoring the driving force at the back of the RSW, the factor of safety of the RSW could be overestimated and its stability is compromised.

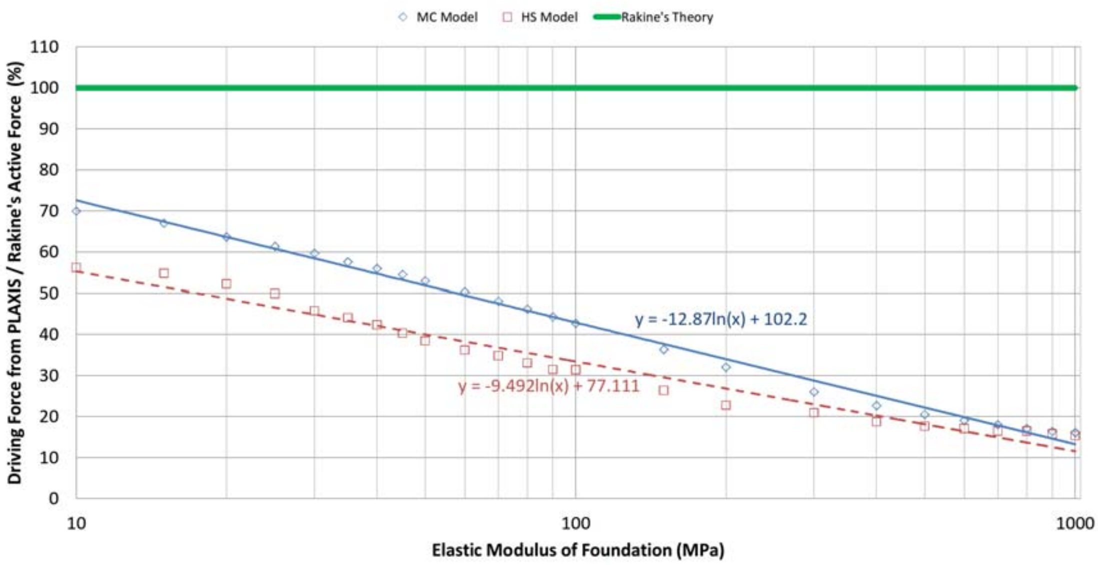

Figure 9. Driving force ratio against various elastic moduli of foundation

The ground settlement of the RSW or the deflection of the SNW is related to the elastic modulus of the foundation material. In Figure 9, the driving force is plotted against various foundation elastic moduli. A linear relationship is obtained between the ratio of the driving force from PLAXIS to the Rankine's active force and the elastic modulus of foundation in a logarithmic scale. The driving force ratio increases from 15% to 70% as the elastic modulus decreases from 1000MPa to 10MPa.

The driving force increases rapidly when the elastic modulus changes from 40MPa to 10MPa. The driving force ratio reaches the maximum value of 70% when the elastic modulus of the foundation is 10MPa. This indicates placing a RSW on a typical soil foundation (e.g. stiff or very stiff clay) will induce the majority of the driving force when this settlement occurs.

If the foundation material is a high-strength rock (i.e. high elastic modulus), ground settlement of the RSW and the deflection of the SNW are negligible. However, a driving force ratio of 15% is still encountered. The driving force is caused by the traffic load of 20kPa and self-weight of the drainage backfill between the SNW and the RSW. Therefore a minimum driving force ratio of 15% always exists even when insignificant settlement and deflection occur.

4 CONCLUSIONS AND RECOMMENDATIONS

In the design of a retaining system consisting of a RSW, a buried SNW and a thin drainage backfill wedge in between them as shown in Figure 1, by ignoring the interaction between the RSW, SNW and the drainage backfill and consequently the earth pressure acting on the back of the RSW the factor of safety of the RSW is overestimated and hence the stability of the RSW is compromised. In this paper, a FEM analysis is carried out to investigate the interaction of an example case of such retaining system and earth pressure acting on the back of the RSW. Construction staging is modelled and parametric study is undertaken considering different foundation material, i.e. different elastic moduli of foundation from 10MPa to 1000MPa.

The following conclusions are obtained based on this study:

- Settlement of the narrow RSW due to its self-weight will consequently cause the deformation of the SNW. The SNW will then push the drainage backfill in between the face of the SNW and the back of the RSW and induce the driving pressure acting on the back of the RSW.
- The driving force ratio increase from 15% to a maximum of 70% when the settlement ratio of the RSW increases from approximately 0.1×10^{-3} to 16×10^{-3}, or when the deflection ratio of the SNW increases from approximately 0.1×10^{-3} to 6×10^{-3}. Rapid increase from 15% to 45% of the driving force ratio occurs when the RSW settlement ratio increases from 0.1×10^{-3} to 2.5×10^{-3}, or when the SNW deflection ratio increases from 0.1×10^{-3} to 1×10^{-3}.
- A negative linear relationship is obtained between the driving force ratio and the elastic modulus of foundation in a logarithmic scale. The driving force ratio increases from 15% to 70% while the elastic modulus decreases from 1000MPa to 10MPa.
- For the case analysed in this paper, significant driving force can be induced by a small amount of ground settlement of the RSW and deflection of the SNW. For example a RSW settlement ratio of 2.5×10^{-3} or a SNW deflection ratio of 1×10^{-3} generally leads to 45% of the driving force ratio.
- In practice elastic modulus of foundation material in the range of 10MPa to 40MPa is not uncommon for this retaining system, which can induce a driving force ratio at the back of the RSW in the range of 70% to 40%. This indicates placing a RSW on a normal soil foundation (e.g. stiff or very stiff clay) will induce the majority of the driving force.

Therefore, driving force with such magnitude is indispensable for the design of the RSW in this retaining system. An appropriate design approach for this RSW sitting in front of the SNW is to carry out a numerical analysis so as to find out the driving force induced by the deformation. It is also recommended the correlations presented in this paper could be referred to estimate the driving forces if similar wall configuration is applied and a detailed numerical analysis of the interaction of the retaining system is not available.

The FEM results indicate the MC model tends to give a larger ground settlement and consequently a larger driving force at the back of the RSW. It is believed that the results of the HS model are more accurate as it uses more accurate stiffness definition than the MC model.

In this study, the impact of the consistency of the drainage backfill in between the RSW and the SNW is not investigated in detail. However, it is anticipated that a loose consistency will reduce the pressure transmission from the SNW to the RSW and the acting force at the back of the RSW like a buffer zone to tolerate the deformation from the SNW.

This study is based on a numerical analysis of an example case. Field monitoring results of such retaining system will assist with the development for the future study.

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