Influence of upper tier on the reinforcement forces in the lower tier in a two-tiered reinforced soil retaining wall

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ABSTRACT: Geosynthetic reinforced soil retaining walls are widely used in recent years due to their successful functional behavior, economy, and ease of construction, compared to conventional reinforced concrete retaining walls. Multi-tiered reinforced soil retaining walls are often considered superior to those with single tier of same heights in terms of efficiency, aesthetics, reliability and economy. Current design approaches such as Federal Highway Administration (FHWA) and National Concrete Masonry Association (NCMA) suggested their guidelines that are empirical and derived on the basis of the offset distance between upper and lower tiers. The interaction between the two tiers is not technically explained. In this paper, the finite element analysis of two tiered MSE wall with various levels of offset distance is carried out using PLAXIS 2D software. The influence of upper tier on the maximum tensile forces in the reinforcement layers of lower tier is studied and compared against the same configuration of walls designed according to NCMA and FHWA design approaches. The critical offset distance (the offset distance beyond which the influence of the upper tier on the reinforcement forces in the lower tier is negligible) of the two tiered retaining wall is studied. It is observed that the magnitudes of reinforcement forces obtained from finite element analysis are less compared to those of other two design approaches.

Keywords: Two tiered MSE wall, reinforcement forces, offset distance, FHWA, NCMA and Plaxis 2D.

1 INTRODUCTION

Geosynthetic reinforced retaining walls are widely used in recent years compared to conventional retaining walls due to their ease in construction, economy, durability and sound performance during earthquakes. The tiered configuration in reinforced walls is generally opted when there is a need for walls with greater height since the reinforcement stresses are high in single walls with greater height. To decrease these stresses, reinforcement density and length of the reinforcements should be increased. This results in increased cost of construction. The tiered configuration is advantageous in terms of economy, aesthetics and increased wall heights. However, offset distances in the tiered configuration results in decreased right of way compared to single walls.

Studies on the performance of multi-tiered reinforced soil retaining walls are limited. The influence of the upper tiers on the reinforcement forces in the lower tiers is not well defined. A study by Yoo and Kim (2002) concluded that for two tiered walls with offset distance ranging from 0.3 to 1.0 times the height of the lower tier, the reinforcement forces in lower tier are influenced by the upper tier and the interaction between upper and lower tiers influences the internal and external stabilities of the wall. Researchers also found that FHWA design approach gives larger reinforcement forces than the NCMA design approach. Leshchinsky and Han (2004) analyzed multi-tier walls numerically. They found that an increase in offset distance reduced the required tensile strength of the reinforcement.

This study deals mainly on how the upper tier influences the reinforcement forces in lower tier under varying offset distance. All the two-tiered MSE walls with varied offsets distances are designed such that external stabilities according to both FHWA and NCMA design approaches are satisfied for the assumed loading conditions. Finite element analysis is used to analyze the same walls. To analyze in finite element method, PLAXIS 2D software is used and for FHWA and NCMA analysis, MSEW (3.0) software is used.

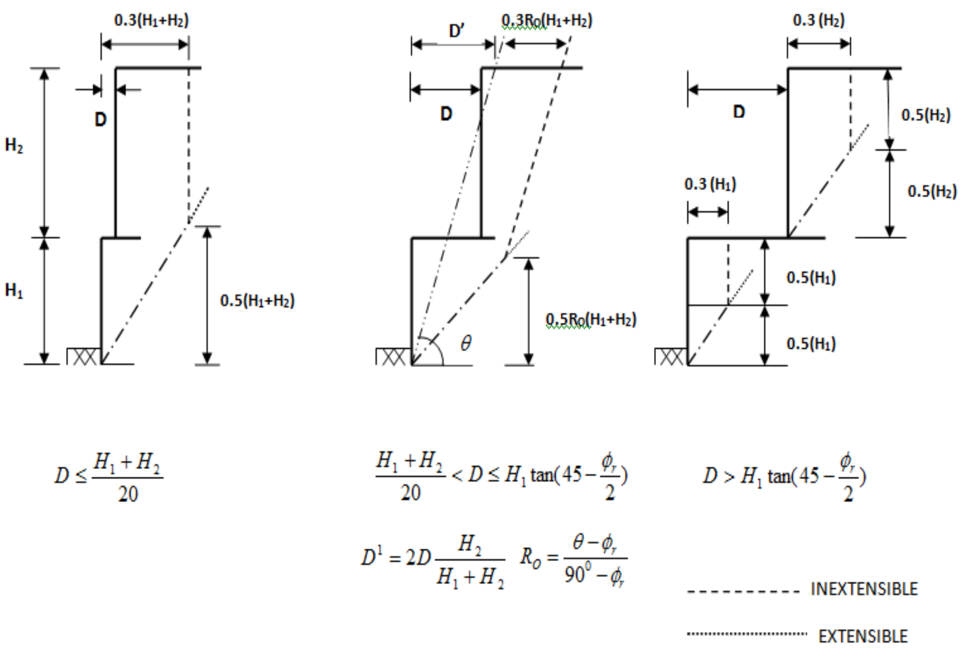
The influence of upper tier on reinforcement forces in lower tier can be quantified in terms of reinforcement forces obtained by subtracting the reinforcement forces of lower tier due to its self-weight alone from the reinforcement forces in the lower tier when upper tier is on it.

2 REVIEW OF DESIGN METHODS FOR TIERED GR-SRW

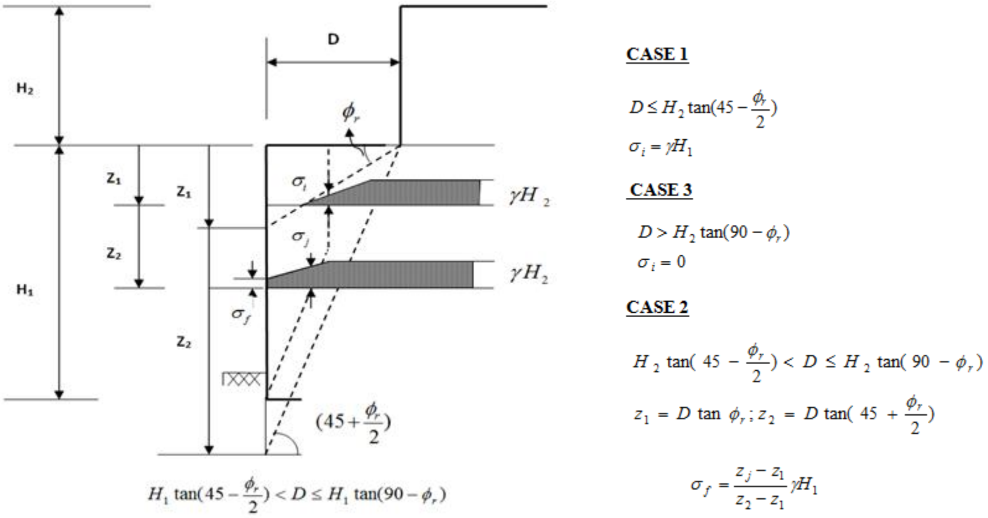
FHWA and NCMA design approaches for tiered MSE walls are considered empirical and geometrically derived based on the offset distance between two tiers. Both the approaches are limited to two-tiered walls. Fundamental principles of these design approaches are discussed below.

2.1 *FHWA design guidelines (FHWA-NHI-00-043)*

In FHWA design approach (Elias and Christopher 1997), internal and external stability calculations are based on offset distance. As per FHWA, the small offset refers to $D \le (H_1 + H_2)/20$ and the design is similar to a single tiered wall with a height of H_1+H_2, but the maximum tension line in the upper tier shifts with the same offset. For intermediate offsets like $(H_1 + H_2)/20 < D \le H_1 \tan(45 - \phi/2)$, the wall is designed as a compound wall for which the maximum tension lines vary with offset distance. For cases like, $D > H_1 \tan(45 - \phi/2)$,maximum tension lines develop separately for the two tiers, yet the influence of upper tier on lower tier effects the internal stability. For cases with $D > H_1 \tan(90 - \phi)$, the two walls are considered to be independent both in external and internal stabilities.



(a) location of maximum tension lines



(b) additional vertical stress

Figure 1. FHWA design guidelines criteria for a two-tier MSE walls (after Elias et al., 2001).

2.2 *NCMA design guidelines*

NCMA design approach (Collin 1997) assumes the upper tier as an equivalent uniform surcharge acting on the lower tier. The internal and external stability calculations for tiered walls are based on offset distance and length of reinforcement in lower tier. According to NCMA, two walls perform independently in internal stability calculations, when the offset distance exceeds reinforcement length in the lower tier..In external stability calculations, the two tiers are considered to be independent when offset exceeds a length equal to sum of reinforcement length and width of Rankine's failure wedge behind the top of the bottom tier reinforced soil block.

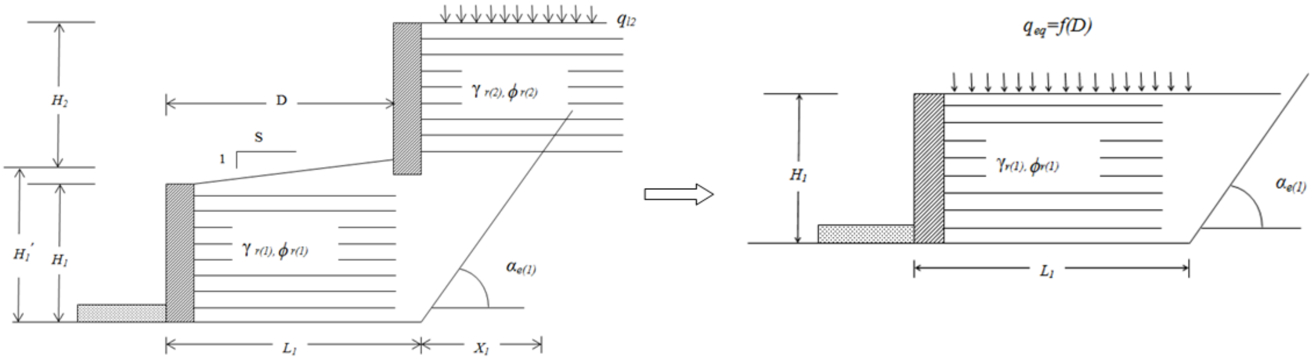


Figure 2. Equivalent surcharge approximation for tiered walls, NCMA (after Yoo et.al 2002).

In the above diagram, H_1 is the height of the lower tier, H_2 is the height of the upper tier, L_1 is length of the reinforcement in the lower tier, L_2 is length of the reinforcement in the upper tier, D is offset distance, S is 500 for flat level backfill between walls, q_{l2} is live load surcharge of upper tier. $\gamma_{r(1)}$, $\phi_{r(1)}$ are unit weight and angle of internal friction of lower tier reinforced soil respectively. $\gamma_{r(2)}$, $\phi_{r(2)}$ are unit weight and angle of internal friction of upper tier reinforced soil respectively and $X_1 = \frac{H_1 + (D/S)}{\tan \alpha_{e(1)}}$ (approximately equal to the width of the Rankine failure wedge at the top of lower tier).

(a) Equivalent uniform surcharge for internal stability calculations:

Case 1: $D <= 0.3L_1$; Use full surcharge $q_{l1} = q_{l2}$, $q_{d1} = \gamma_{r(2)} H_2$

Case 2: $0.3L_1 < D < L_1$; Use percentage of surcharge $q_{l1} = \frac{L_1 - D}{L_1} q_{l2}$, $q_{d1} = \frac{L_1 - D}{L_1}(\gamma_{r(2)} H_2)$

Case 3: $D >= L_1$; No influence $q_{l1} = 0$, $q_{d1} = 0$

(b) Equivalent unifrom surcharge for external stability calculations:

Case 1: $D <= (L_1+0.5X_1)$; Use full surcharge $q_{l1}= q_{l2}$, $q_{d1} = \gamma_{r(2)} H_2$

Case 2: $(L_1+0.5X_1)< D< (L_1+X_1)$; Use percentage of surcharge $q_{l1} = \frac{L_1 + X_1 - D}{X_1} q_{l2}$,

$$q_{d1} = \frac{L_1 + X_1 - D}{X_1}(\gamma_{r(2)} H_2)$$

Case 3: $D >= (L_1+X_1)$; No influence $q_{l1} = 0$, $q_{d1} = 0$

Note: $0.3L_1$ and $0.5X_1$ are arbitrary but empirically based geometric limits to ensure a conservative surcharge approximation.

3 MAIN STUDY

This study deals mainly on how the upper tier influences the reinforcement forces in lower tier under varying offset distance. The offsets considered in this study include the classification of offsets according to FHWA and NCMA which are shown in Table 1. All the two tiered MSE walls with varied offsets distances are designed such that external stabilities according to both FHWA and NCMA design approaches are satisfied for the considered loading conditions. Finite element analyses is utilized to analyze the same walls. To analyze in finite element method, PLAXIS 2D software is used and for FHWA and NCMA analysis, MSEW (3.0) software is used.

Table 1. Offset considered according to FHWA and NCMA design guidelines.

FHWA condition	**Offset, D**	**NCMA condition**	**Offset, D**
$D < (H_1 + H_2)/20$	0.4 m	$D<0.3L_1$	3.5 m
$D < H_1 \tan(45 - \phi/2)$	3.5 m	$0.3 L_1<D < L_1$	4 m
$D > H_1 \tan(45 - \phi/2)$	4 m	$D >L_1$	15 m
$D < H_1 \tan(90 - \phi)$	9 m	$D > L_1+0.5 X_1$	16.5 m
$D > H_1 \tan(90 - \phi)$	12 m	$D >L_1+X_1$	19.5 m

Where, H_1 = Height of bottom tier = 7m, L_1 = Length of reinforcement in lower tier =14m, and X_1 = width of Rankine failure plane at the top of the lower tier = 3.64m

3.1 *Wall geometry*

Two-tiered MSE wall of same wall height of 7m is considered for the present study. A rigid foundation is assumed for this study to avoid the effect of yielding foundation. A dead surcharge q_{dl} of 40kPa and a live surcharge q_{ll} of 40kPa is applied on the top of the upper tier. A vertical strip load P_V of 110kN/m is applied on a footing of width 2m and height 1.5m at a distance of 1.5m from the wall face of the upper tier. A horizontal strip load P_H of 30kN/m is acting at the base of the footing. Design considering these loading conditions yields 7m and 14m as lengths of upper and lower tier reinforcements respectively. Figure 3 shows the two tiered wall with loading conditions used for this study. As the aim of this paper is to present the influence of upper tier on reinforcement forces of lower tier, reinforcement forces corresponding to other loading conditions are presented elsewhere. Results corresponding to this study are discussed in further sections.

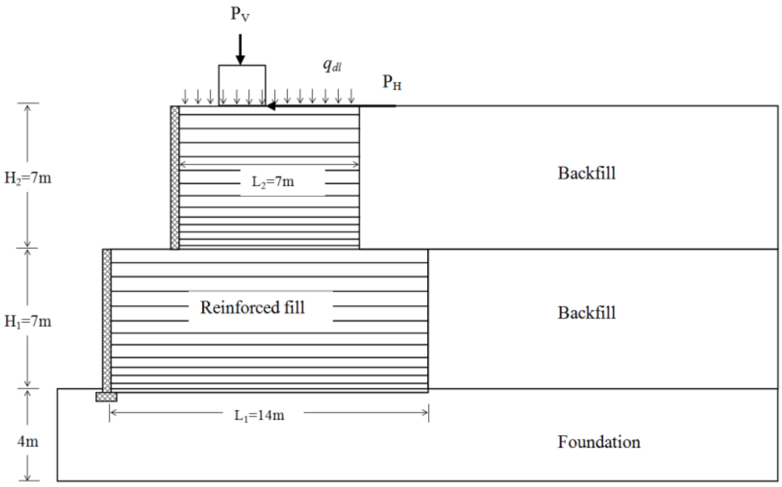


Figure 3. Schematic diagram of the model.

3.2 *Finite Element modelling*

In this study, the two-dimensional finite element program PLAXIS 2D was used to perform the numerical analyses of the reinforced soil walls. Rock foundation of length 36m and depth 4m is considered.. Staged construction is adopted for this study in order to replicate field construction. Drained condition is assumed throughout the study.

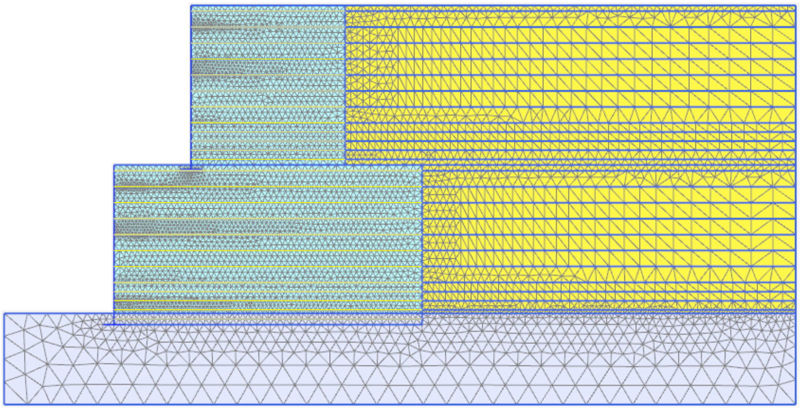


Figure 4. Finite element mesh.

The corresponding material properties assigned to backfill, reinforced soil and foundation soil are shown in Table 2. Backfill soil, reinforced soil and foundation soils are modeled using Mohr-Coulomb model. Layout of geogrids, interfaces, plates and props and concrete footing is created and properties are assigned. Plates are connected using hinged connections. Material type adopted for geogrids is elastoplastic type. Geogrids of tensile strength 110kN/m are used in this study. Reinforcement layers at the bottom of two tiers are closely spaced. Vertical spacing along the depth of wall is not constant.

Table 2. Material properties

Properties	*Backfill*	*Reinforced fill*	*Foundation*
Unit weight, γ (kN/m^3)	18	20	25
Cohesion, c (kPa)	1	1	400
Angle of internla friction, φ (degrees)	30	35	30
Modulus of elasticty, E_s (kPa)	32000	35000	80000

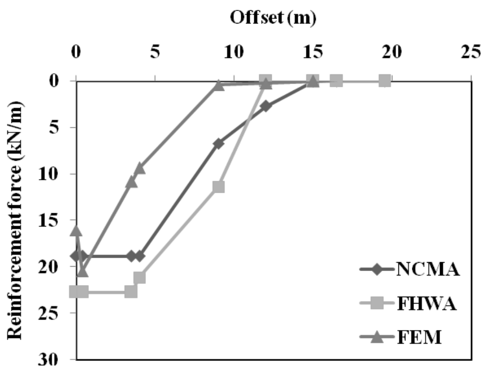
Horizontal strip load of intensity 30kN/m, acting towards the face of the wall is assigned at the base of the footing. A uniform surcharge load of 40 kN/m^2 is acting on the top of the upper wall. Later in the calculation mode, a stage wise phase construction is adopted.

4 RESULTS AND DISCUSSION

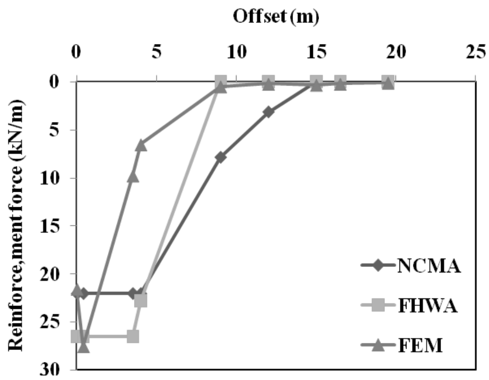
The influence of upper tier on the reinforcement forces in the lower tier, the critical offset distance and the interaction between the upper and lower tier are discussed in this section.

4.1 *Critical offset distance*

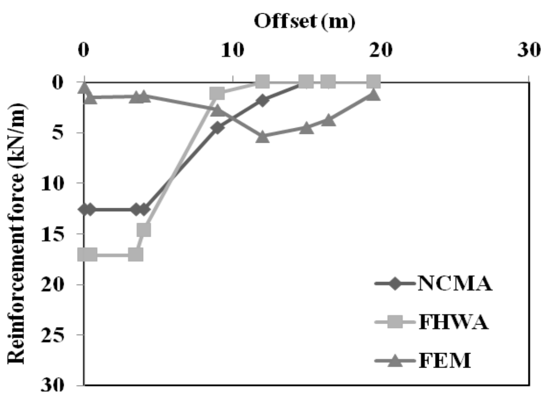
The critical offset distance according to FHWA approach is 9.99m ($H_1 \tan(90 - \phi)$) and NCMA approach is 14m (length of reinforcement in the lower tier) for this study. Figures 5, 6, 7 shows the variation of reinforcement forces in lower tier along offset distance at a depth of 0.25m, 3.75m and 6.75m respectively in the lower tier. From FE analysis, the influence of upper tier on the reinforcement forces of top and middle layers of lower tier are found negligible from an offset distance of 9m which can be considered as critical offset distance. However, the influence of upper tier on bottom layers of lower tier are not negligible even after the critical offset distance. In this study, both FHWA and NCMA design approaches overestimate the critical offset distance.



(a). 0.25m depth



(b). 3.75m depth



(c). 6.75m depth

Figure 5. Variation of reinforcement forces in lower tier along the offset distance at 0.25m, 3.75m and 6.75m depths respectively.

4.2 *Reinforcement forces*

The influence of upper tier on reinforcement forces in lower tier can be quantified in terms of reinforcement forces that are obtained by subtracting the reinforcement forces of lower tier due to its self weight alone from the reinforcement forces in the lower tier when there is upper tier on it. Figure 6 shows that nearly 50 percent of reduction in reinforcement forces when offset distance increased from small offset 0.4m to moderate offset distances like 3.5 and 4m after which there is negligible influence of upper tier on the top and middle layers of lower tier for the range of offsets considered in this study.

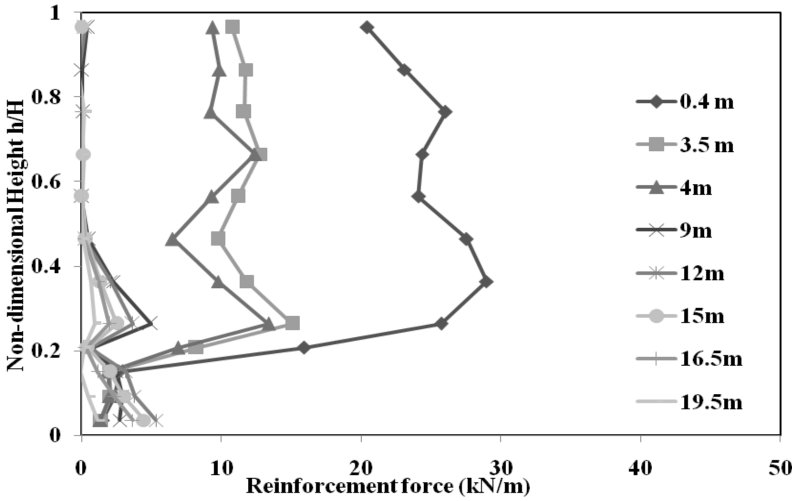
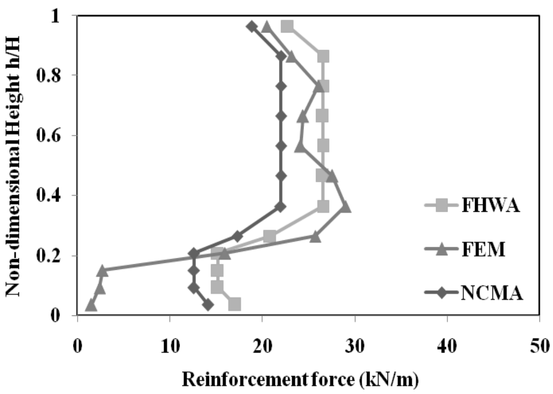
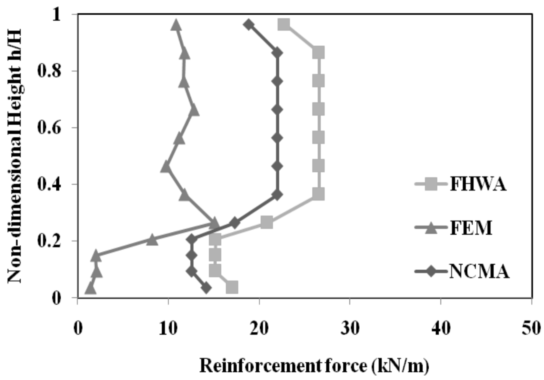


Figure 6.Variation of reinforcement forces in lower tier due to upper tier.

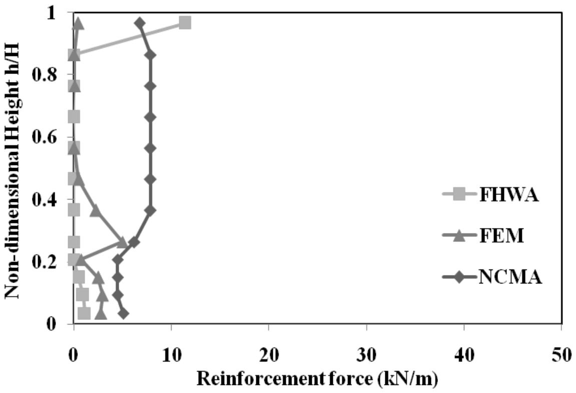
Figure 7 shows the influence of upper tier along the depth of lower tier for 0.4m, 3.5m and 9m offset distances. Both FHWA and FHWA overestimates the influence of upper tier for all offsets considered in this study except for very short offset distance 0.4m.When compared among two design guide lines, FHWA overestimates up to 9m offset from where NCMA overestimates the reinforcement forces.



(a). 0.4m offset



(b). 3.5m offset



(c). 9m offset

Figure 7. Variation of reinforcement forces in lower tier for 0.4m, 3.5m and 9m offsets respectively.

5 CONCLUSIONS

The critical offset distance for two tiered MSE wall is overestimated by both the design guide lines. Moreover, the critical offset distance criteria according to NCMA design guide lines where offset distance is a function of length of reinforcement in lower tier is not reliable. The influence of upper tier on reinforcement forces in lower tier is maximum for very short to intermediate offset distances. For larger offset distances the bottom layers of lower tier are effected even after critical offset distance.

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