NUMERICAL MODELING OF REINFORCED SOIL SEGMENTAL WALL UNDER SURCHARGE LOADING

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ABSTRACT

This paper outlines the finite element procedure for simulating the performance of a reinforced soil segmental (modular blocks) wall. Analyses were performed using a software code which is developed in FORTRAN and validated for reported case histories in the literature. The material properties of the wall like backfill, foundation, modular concrete fascia blocks and reinforcement were expressed using linear elastic models. A series of parametric studies was conducted to identify effects of reinforcement, stiffness and Poisson’s ratio of backfill and foundation strata on the performance of the wall. Increased stiffness of backfill and foundation improves the performance of the wall by restraining the front face deformation. The design charts for deflections at top and bottom and also, height of rotation are developed in the current work by varying the stiffness of backfill and foundation. These charts are useful to the designer to choose appropriate backfill and also, to ascertain the suitability of available foundation for the construction of wall, considering codal provisions regarding deformation limits at the front face of the wall.

Key words: reinforced earth wall; finite element analysis; yielding foundation; serviceability criteria; uniform surcharge; segmental wall.

1. INTRODUCTION

The reinforced soil structure has gained increasing popularity for replacing the conventional retaining wall. As a result, various procedures have been proposed for designing the said structures [1]. However, the currently used design procedures could only be regarded as semi-empirical. They are mostly based on the limit equilibrium method (LEM) which
evaluates the internal and external stabilities of the structures at their ultimate strength condition. Due to its inability to consider the operational conditions of the structures, such as the construction sequence, soil structure interaction and load-displacement relationship. LEM-based design has to be encompassed with high factor of safety. The study by Claybourn and Wu [2], which evaluated the most commonly used LEM-based design procedures, clearly demonstrated this fact and it directly reflects our general lack of understanding of the performance of reinforced soil structures.

When compared with LEM, the finite element method (FEM) more powerful analytical tool for solving the boundary value problems. It renders informations such as the deformation and stress-strain distribution in the structure subject to complex geometries, boundary and loading conditions. These informations are highly required in designing the important civil engineering structures. Also, the design of any structure needs to consider two limit states, the serviceability and ultimate limit state. In case of reinforced soil the serviceability is checked at working conditions to ensure that, it will retain the characteristics necessary for it to fulfill its function throughout its life without the need for abnormal maintenance. The ultimate limit state relates to all potential collapse mechanisms that can be identified, to major damage or deformations in excess of acceptable limits.

Also, the behaviour of a reinforced soil retaining structures constructed on a rigid foundation has been extensively investigated both experimentally and theoretically in past and many current design criteria’s are based partly on this research [3-19]. However, the behaviour of these reinforced soil walls constructed on soft or yielding foundations has received limited attention [20-30] and many questions still remain as to the performance and response of these structures. The overall behaviour of a reinforced earth wall constructed on yielding foundation, including a review of the vertical stress and displacement at the base of the wall, the horizontal stress behind the wall facing and strain pattern in the reinforcement, has not been examined. Hence, the current investigation deals with a short-term analysis of a reinforced soil wall constructed on a yielding foundation and analyses the key factors influencing the wall behaviour.

2. PARAMETRIC DETAILS

The analysis of reinforced earth wall is carried out by considering the different parameters which are discussed below.

2.1 Typical cross section

The typical cross section of the earth wall along with the underlying foundation strata is shown in Fig. 1, in which ‘b’ denotes the roadway width, and ‘H’ denotes the wall height. The underlying foundation strata are assumed to be a semi-infinite granular formation. The modular concrete blocks with reinforcement attached to the blocks are assumed in the investigation. A concrete footing protection block was cast at the toe of the wall at the early stages of construction to prevent the base of the wall from significantly pushing out.
Fig. 1 Typical cross-section of reinforced earth wall resting upon the semi infinite foundation strata

2.2 Soil in earth wall

Three types of granular (c-\(\phi\)) soils are considered for the construction of the earth wall. The engineering properties of these three types of embankment (backfill) material are presented in Table 1. [31].

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Soil designation</th>
<th>Soil modulus, (E) (kPa)</th>
<th>Poison’s ratio ((m))</th>
<th>Unit weight, (\gamma) (KN/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E(_1)</td>
<td>1.00E+05</td>
<td>0.300</td>
<td>18.5</td>
</tr>
<tr>
<td>2</td>
<td>E(_2)</td>
<td>5.00E+04</td>
<td>0.275</td>
<td>18.0</td>
</tr>
<tr>
<td>3</td>
<td>E(_3)</td>
<td>1.00E+04</td>
<td>0.250</td>
<td>17.5</td>
</tr>
</tbody>
</table>

2.3 Soil in the Foundation Strata

Six types of soil are considered in the foundation strata. The engineering properties of these six types of soil are presented in Table 2. [31].

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Soil designation</th>
<th>Soil modulus, (E) (kPa)</th>
<th>Soil density, (\gamma) (KN/m(^3))</th>
<th>Poison’s ratio ((m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F(_1)</td>
<td>1.00E+02</td>
<td>16.5</td>
<td>For each value of (E) shown in column-03, three</td>
</tr>
<tr>
<td>2</td>
<td>F(_2)</td>
<td>1.00E+03</td>
<td>17.0</td>
<td>values of Poison’s ratio of</td>
</tr>
<tr>
<td>3</td>
<td>F(_3)</td>
<td>1.00E+04</td>
<td>17.5</td>
<td>foundation strata namely</td>
</tr>
<tr>
<td>4</td>
<td>F(_4)</td>
<td>1.00E+05</td>
<td>18.0</td>
<td>0.30, 0.35, and 0.40 are</td>
</tr>
<tr>
<td>5</td>
<td>F(_5)</td>
<td>1.00E+06</td>
<td>18.5</td>
<td>considered.</td>
</tr>
<tr>
<td>6</td>
<td>F(_6)</td>
<td>1.00E+07</td>
<td>19.0</td>
<td></td>
</tr>
</tbody>
</table>
2.4 Steel reinforcement

The reinforcement considered in the analysis is galvanized iron strips of 4 cm wide and sectional area of 1.0 cm$^2$ placed at 50 cm vertical spacing. The elastic properties of reinforcement assumed in the analysis are: modulus of elasticity ($E$) 200 GPa, and poison’s ratio ($m$) 0.30. [32-33].

2.5 Fascia modular concrete blocks

A vertical column of the modular concrete blocks as a fascia element is provided to support the reinforced system. The fascia element is 20.0 cm thick with a concrete of the grade M25, hence its material properties are: $E=2.5\times10^7$ kPa, $\gamma=25$ Kn/m$^3$ and $\mu=0.15$ [16].

2.5 Surcharge loading (q)

A uniform surcharge of magnitude 40 kPa for the considerations to the additional traffic road, extending over the full width of roadway is considered in the analysis [34].

3. FINITE ELEMENT IDEALIZATION

The software developed in FORTRAN for the analysis of reinforced earth retaining wall and tested for reported case histories in the literature is used to conduct the numerical analysis. The reinforced earth wall with modular fascia concrete blocks was idealized as two-dimensional and a plain-strain FE analysis was performed. From Fig. 1, it is easy to recognize that the system under consideration has a vertical axis of symmetry; hence, it is adequate to analyze only half section as shown in Fig. 2. The boundaries of the section being investigated are based on the following assumptions.

i) The boundary defined by the vertical axis of symmetry represents a boundary with horizontal displacement being restrained.

ii) The infinite domain of the foundation strata is curtailed vertically at a depth ‘D’, and the boundary so formed is assumed to be restrained horizontally as well as vertically.

iii) The infinite lateral boundary of the foundation strata on the left is curtailed at a distance ‘L’, and resulting boundary is assumed to be restrained in horizontal direction.

The zone so developed is idealized through square elements of size 0.5m by 0.5m. The backfill of earth wall and foundation soil have been discretized using 2D four nodded isoparametric plane strain quadrilateral element. The geometry nodal point locations, loading and the coordinate system for this element are shown in Fig. 3. Every element is defined by four nodal points having two degrees of freedom at each node, i.e. translation in $X$ and $Y$ directions. A unit thickness is assumed for the element. The material properties as a input for this element, for isotropic elastic case, are soil modulus ‘$E$’, Poison’s ratio ‘$m$’ and soil density ‘$\gamma$’.

The reinforcing elements have been modeled as two-dimensional line element. It is uniaxial tension/compression element with two degrees of freedom at each node (Translation in nodal $X$ and $Y$ directions). No bending of element is considered. The element is defined by two nodal points. The cross sectional area, and material properties ($E$, $m$) are the input for this element. The displacement direction for the line element is assumed to be linear.

The fascia element have the behavior of that of an articulated column, hence it is represented through two nodded elements with only axial mode of deformation. In addition for in depth investigation between the line elements representing the fascia elements and the adjoining wall surface, the interface elements are incorporated. As the fascia elements are line elements,
the poison ratio (μ) does not appear in the formation of the element characteristics. Pilot run of the problems indicate that for a wide range of the interface moduli (Ks, Kn); the response is more or less unaffected. Hence the following typical values for them are assumed in the current investigations for the formulations of interface element i.e. Ks=90 kPa and Kn=60 kPa.

It was found that, the common approach of providing equally spaced truncated reinforcement with reinforcement length (L) to wall height (H) ratio, L/H equal to 0.7, provides a relatively efficient distribution of reinforcement force. In contrast, the approach of varying reinforcement spacing in an attempt to mimic the horizontal stress distribution provided to be less efficient and is not recommended. Varying reinforcement length, i.e. reinforcement extended to the zero force line, did not provide any significant improvement in force distribution relative to the truncated reinforcement of L/H=0.7. Hence, in the current investigation, the minimum ratio L/H=0.7 is maintained [35-36].

Fig. 2 The details of symmetrical section considered in the analysis

Fig. 3 Finite element idealization for reinforced wall system with modular concrete fascia blocks
3.1 Details of Idealization Scheme

Full information of the idealized system, considered in analysis is presented in Table 3. The details of the four material types presented in Table 3 are, backfill material used for the construction of earth wall, foundation material assumed below the earth wall, the steel reinforcement used as reinforcement in the earth wall and the modular concrete blocks used to support the fascia of the wall.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>H (m)</th>
<th>b (m)</th>
<th>Number of elements</th>
<th>Total no. of elements</th>
<th>Total no. of boundary nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
<td>12.0</td>
<td>180</td>
<td>855</td>
<td>156</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>15</td>
<td>1221</td>
<td>1123</td>
<td>103</td>
</tr>
</tbody>
</table>

4. FINITE ELEMENT ANALYSIS

The reinforced earth wall is discretized as discussed in section 3. The parametric investigations are carried out by varying the properties (vide Table 1 and Table 2) of embankment and foundation strata. The response derived for deflected front face profile of wall for wall height 7.5m and roadway width 12.0m, considering self-weight of wall are presented in Figs. 4a-i. The modulus of elasticity of reinforcement equal to 200 GPa and sectional area of 1.0cm£ is kept constant for all investigations.

The stiffness values of backfill and foundation are expressed in ‘kPa’ as shown in Figs. 4a-i. Each figure shows the variation of front face deflections for a particular value of stiffness (kPa) and Poisson’s ratio of embankment and by varying the stiffness of foundation strata to seven types and keeping Poisson’s ratio of foundation constant as shown in legend. The outward deflections from the vertical line of the wall at the base are plotted as negative values and inward deflections at the top are plotted as positive values.
Fig. 4 (a-i) Response details of front face deflected profile of earth wall for $H=7.5\text{m}$, $b=12\text{m}$
4.1 Wall resting on weak foundation

The results presented in Figs. 4a-i, show that, so long as the foundation stiffness represented by the value of ‘$E$’ is less than that of backfill (i.e. wall resting on weak foundation), the vertical face of the wall deflects in a manner which is shown schematically in Fig. 5a. The deflected profile as shown in Fig. 5a. is characterized by inward deflection at the top of the wall and outward deflection at the base; thereby, it has point of rotation over the wall height. The profile shape is approximately parabolic and if, its theoretical details are required, then over the data, the parabolic expression could be fitted by considering the point of rotation and its location and the amount of deflection at the top and the base of the wall. Hence to define the complete behavior of deflected profile, it needs to define the maximum deflection at top and base and also the height of rotation.

4.2 Wall resting on strong foundation

In case of the foundation soil having value of stiffness ‘$E$’ equal to or more than that of the reinforced backfill (i.e. wall resting on strong foundation), it is observed that, the deflection at the top is in the inward direction and significant and the deflection at the base is almost zero. Thereby, it has point of rotation over the wall height. The profile shape is approximately parabolic. The apex of the parabola defines the maximum outward deflection suffered by the wall (Fig. 5b). Hence for strong foundation to check the codal serviceability requirement, the deflections at top, deflection at bulge and its location is necessary. The maximum deflections at bulge and its location for various wall heights will be reported in the next paper (part-II).

As reported in section 4, the analysis of reinforced earth wall is carried out for self-weight, is also carried out for a uniform surcharge of 40 kPa extending over a full width of the wall. The front face deflections at top and base and the height of rotation from base in percentage height are plotted in Figs. 6a-i, for the entire range of three types of embankment and seven types of foundations. In each Figure the stiffness and Poison’s ratio of embankment is kept constant. Front face deflections are plotted by varying the stiffness of foundation to six types. First three series shows the variation of front face deflections by varying Poison’s ratio of foundation to 0.30, 0.35 and 0.40 for self-weight of the wall. Next three series shows the variation of front face deflections by varying the Poisson’s ratio of foundation to 0.30, 0.35 and 0.40 for a constant surcharge of 40 kPa extended over full width of the wall.

Fig. 5. Response of wall. (a) resting on weak foundation and (b) resting on strong foundation
Embankment
E=1.0E+05, m=0.30

Embankment
E=5.0E+04, m=0.275

Embankment
E=1.0E+04, m=0.25
(d) Embankment $E=1.0\times10^5$, $m=0.30$

(m=0.30,q=0.00)
(m=0.35,q=0.00)
(m=0.40,q=0.00)
(m=0.30,q=40.0 Kpa)
(m=0.35,q=40.0 Kpa)
(m=0.40,q=40.0 Kpa)

(e) Embankment $E=5.0\times10^4$, $m=0.275$

(m=0.30,q=0.00)
(m=0.35,q=0.00)
(m=0.40,q=0.00)
(m=0.30,q=40.0 Kpa)
(m=0.35,q=40.0 Kpa)
(m=0.40,q=40.0 Kpa)

(f) Embankment $E=1.0\times10^4$, $m=0.25$

(m=0.30,q=0.00)
(m=0.35,q=0.00)
(m=0.40,q=0.00)
(m=0.30,q=40.0 Kpa)
(m=0.35,q=40.0 Kpa)
(m=0.40,q=40.0 Kpa)
**Fig. 6** Response details, (a, b, c) front face deflections at the top, (d, e, f) deflections the base, and (g, h, i) the height of rotation, for H=7.5m and b=12.0m.
The observations noted from Figs. 6a-i, show that, the response derived for the 7.50m wall height and 12.0m road width, for above parametric investigation, with self-weight as well as with a surcharge of 40.0 kPa remains same. But the magnitudes of inward front face deflections at top, in case of weak foundation increase by 30% to 40% due to surcharge and for strong foundation the front face deflections at top are also, inward and they increase 50% to 60%.due to surcharge. The outward front face deflections at base for weak foundation increase by 30% to 40%.due to surcharge and for strong foundation they tend to zero. For weak foundation, the front face deflections are sensitive to Poison’s ratio, but for strong foundation, they are insensitive to Poison’s ratio.

The height of rotation which is expressed in terms of percentage wall height is observed to be almost constant for weak and strong foundation and it varies from 70% to 75% for self-weight of wall and 75% to 85% for a surcharge of 40kPa.

11. SUMMARY AND CONCLUSIONS

The physical data presented in this paper and the lessons learnt after investigating the response of a reinforced soil with segmental wall are of value to researchers engaged in developing better understanding of reinforced soil wall behavior. Specific important conclusions in this regard are summarized below.

1. When the wall resting on strong foundation, the rotation of reinforced earth wall is observed at a particular height, imparting inward deflection at the top of wall and outward deflection at the base of wall.
2. In case of wall resting on strong foundation also, the rotation of reinforced earth wall is observed at a particular height. But, inward deflection at the top of wall is significant and the deflection at the base of wall tends to zero.
3. In case of weak foundation, the response of the wall is sensitive to Poison’s ratio. The front face deflections are changing as the Poison’s ratio increases. But for strong foundation, the response is insensitive to Poison’s ratio.
4. Design correlations have been plotted using finite element method for three types of embankments and seven types of foundation strata for different parameters like, deflections at top, deflections at base, height of rotation. This will help the designer to choose appropriate backfill and also, to ascertain the suitability of foundation for the construction of wall considering codal provisions regarding deformation limits at the front face of the wall.

REFERENCES

