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Computer-Aided Design of Reinforced Earth Walls

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Abstract: The design of an earth reinforced wall will inevitably involve an enormous amount of repetitive design calculations that are quite tedious and time consuming. This paper presents the development and verification of a computer-aided design program for reinforced earth walls formed by precast concrete facing panels. The program is written in advanced BASIC that is tailored for use on IBM compatible micro-computers. The program uses the presented input data to perform both external and internal stability analyses and produces the appropriate and safe design parameters. For external stability, the program computes the safety factors for (a) sliding on the base, (b) overturning about the toe, and (c) bearing capacity failure. Once the program deems the wall to be safe externally, it provides various alternative solutions for the strip reinforcement system. Considering the selected system, an internal stability analysis is conducted. For this part, the program calculates the safety factors for (a) reinforcement rupture, (b) tensile failure of reinforcement, (c) tensile failure of connections, (d) pullout of reinforcement, and (e) corrosion failure. The program automatically readjusts the design to improve and fulfill all the stability criteria. Finally, the program provides design summaries of the safest wall.

Key Words: Reinforced Earth, Geotechnology, Computer-aided Design

Introduction

Reinforced earth is a construction material consisting of soil strengthened by the inclusion of tensile elements such as metal rods or strips, nonbiodegradable fabrics and most recently the geosynthetic material which was introduced to the civil engineering profession. The materials used in manufacturing geosynthetics are primarily obtained from the plastic industry, i.e. they are primarily polymers such as polyester, polyethylene, polypropylene, polyvinyl chloride, nylon, and chlorosuphonated polyethylene. The family of geosynthetics includes the following: geotextile, geogrid, geonet, geomembrane, and geocomposite. Each type of geosynthetic performs one or more of the following functions: drainage, filtration, separation, and/or reinforcement.

In many cases where an existing or proposed slope is unstable or flattening of the slope is not feasible, earth retaining structures become a necessity. In recent years, some of the most significant advances in geotechnology have been in the field of earth reinforcement . In the past two decades several techniques and design procedures have been the subject of much interest and continuing research (Schlosser and Long, 1974; Jones, 1984 and Koerner, 1990)

While classical methods of designing reinforced earth were developed analytically, other methods, based on field observations have received much attention (Laba and Kennedy, 1986 and Thamm *et al.*, 1990). Additionally, other techniques based on reliability theory have been introduced (Basma and Al-Harthy, 1996). However, and regardless of the design approach used, it is a fact that the design of reinforced earth walls will unavoidably entail a large amount of design calculations which are time consuming and tedious. For this reason and because of the prevalence of reinforced earth walls over other types of earth retaining structure, a computer program for the design of these type of walls is a real need. This paper will, therefore, concern itself with the development of a computer program for the design of reinforced earth walls. This program, tailored for use on microcomputers, is written in advanced BASIC language.

General Description of Reinforced Earth Walls: An earth reinforced wall system is generally made up of three basic components: (1) reinforcement, (2) backfill soil, and (3) facing elements. The reinforcing material can be of broad nature ranging from metallic to non-metallic. The reinforcement geometry can also be widely categorized as strips, sheets, fibers, rods and grids. The type of backfill soil used has an important role in the performance of the reinforced earth system. Commonly, a well graded granular soil is preferred to meet stress transfer, drainage and durability requirements. Facing elements are generally used to provide support for the retained soil at the face and to prevent erosion and slipping of steep faces. Available facing elements include concrete panels, welded wire mesh, metallic sheets and plates. Fig. 1 shows a 3D schematic diagram of a reinforced earth wall.

Design Procedure for Reinforced Earth Walls: The design of reinforced earth walls is basically controlled by the external and internal stability of the wall. For external stability, the wall must be safe for sliding because of the lateral pressure of the soil retained by the wall, it must resist overturning about the toe and must be safe against bearing capacity failure. For internal stability on the other hand, the reinforced soil wall requires that the reinforcement neither ruptures nor pulls out. The following subsections present the design procedure considered for the reinforced wall to be safe externally and internally. This procedure is basically adopted from the report published by NCHRP (NCHRP, 1987). Furthermore, the reinforced walls considered herein are generally of low height (up to 8 meters) with sloping backfill.

ternal Stability: The external stability of the reinforced rth wall depends on the capability of the nforced soil mass to resist the external forces. These rces include the horizontal earth pressure from the ckfill soil and applied loads on the top of the

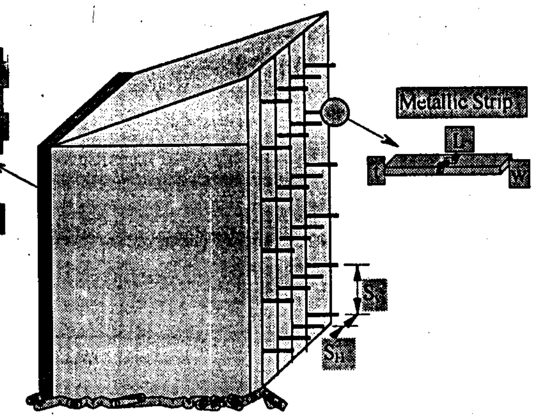


Fig. 1: Schematic Diagram of a Reinforced Earth Wall

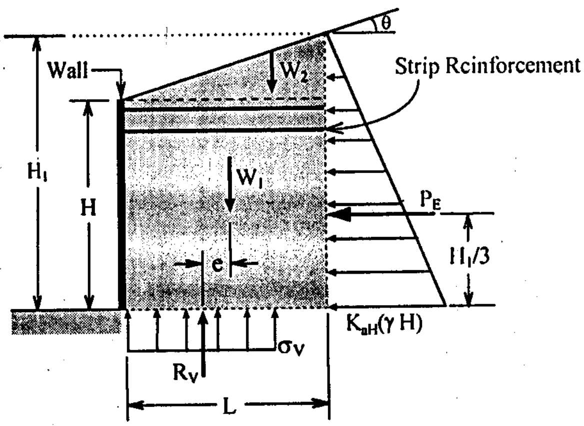


Fig. 2: Forces for External Stability Analysis

wall without failing by one of the following mechanisms: (a) sliding along the base or any other plane; (b) overturning about the toe,; (c) bearing capacity failure of the foundation. The forces that must be considered in the design are shown in Fig. 2. It is worth noting that for the reinforced earth structure in this Fig. the active earth pressure P_E should be parallel to the slope. This indicates that there is a downward component of P_E which acts as a resisting force. In subsequent analysis, however, this latter force is neglected thus producing a conservative design.

Using Coulomb's theory, the active earth pressure coefficient can be calculated by:

$$K_{aH} = \cos^2\theta \quad \frac{\cos\theta \quad \sqrt{\cos^2\theta \quad \cos^2\phi_b}}{\cos\theta + \sqrt{\cos^2\theta \quad \cos^2\phi_b}} \tag{1}$$

where θ is the slope angle and ϕ_b is the internal friction angle of the backfill.

Sliding Along the Base: The length L of the reinforcement should be computed in such a way that the safety factor is at least = 1.5. Thus,

$$SF_S = \frac{(W_1 + W_2)\tan\phi_b}{P_E} \geq 1.5 \tag{2}$$

where SF_S = sliding safety factor; $P_E = \frac{K_{aH}\ \gamma\ H_1^2}{2}$; $W_1 = LH\gamma$; and $W_2 = \gamma\left[\frac{L\ (H_1\ \ H)}{2}\right]$.

Overturning about the Toe: A factor of safety greater than 2.0 is required, therefore,

$$SF_{OV} = \frac{\sum M_R}{\sum M_{OV}} \geq 2.0 \tag{3a}$$

where $\sum M_R$ = sum of resisting moments = $W_1\left(\frac{L}{2}\right) + W_2\left(\frac{2L}{3}\right)$; $\sum M_{OV}$ = sum of overturning or driving moments = $P_E\left(\frac{H_1}{3}\right)$. Substituting in Eq. (3a) the result becomes:

$$SF_{OV} = \frac{\frac{L^2H\gamma}{2} + \gamma L^2\left(\frac{H_1 - H}{3}\right)}{\frac{K_{aH}\gamma H_1^3}{6}} \geq 2.0 \tag{3b}$$

Bearing Capacity Failure: The vertical reaction at the base is computed as

$$R_V = W_1 + W_2 \tag{4}$$

This force is at an eccentricity e from the centerline which is calculated by

$$e = \frac{\sum M_{centerline}}{R_V} = \frac{P_E\left(\frac{H_1}{3}\right) - W_2\left(\frac{L}{2} - \frac{L}{3}\right)}{R_V} \tag{5}$$

For the wall to be safe against bearing capacity failure the eccentricity e should be within the middle third of the length L i.e. $e \leq \frac{L}{6}$.

Internal Stability: The forces considered for internal stability of layer I of the reinforcing system are shown in Fig. 3. In this Fig. the height $H_{2i} = (H_i + H_{1i})/2$. The calculations for the internal stability of layer I at a depth of H_i below the top of the wall are presented below.

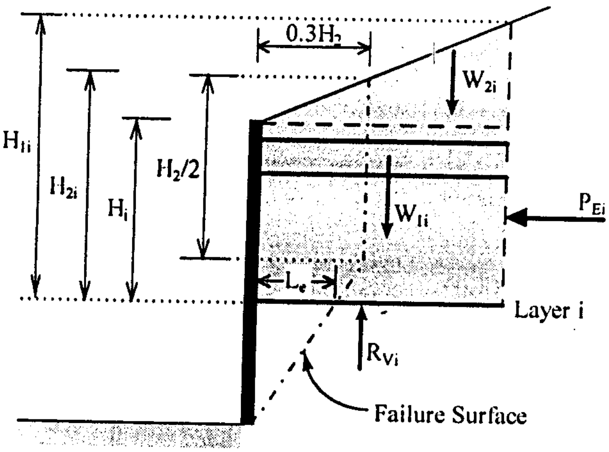


Fig. 3: Forces for Internal Stability of the Reinforcement Layer I

Rupture of Reinforcement: The vertical stress at the level of layer I is calculated as

$$\sigma_{V\,Bi} = \frac{R_{Vi}}{L - 2e_i} \tag{6}$$

where R_{Vi} and e_i are calculated by Eqs. 4 and 5 for Layer i. In this case, if $e_i < 0$, a conservative value of e = 0 is used.. The horizontal earth pressure in the reinforcement layer at this depth is computed by

$$\sigma_{Hi} = K\,\sigma_{V\,Bi} \tag{7}$$

where K is the earth pressure coefficient which can be determined from Fig. 4(a). The boundary values for K are: K_a at z = 0 and K_o at z = 20 ft. Therefore, for H_{2i} > 20 ft, $K = K_a$, and for $0 \le H_{2i} \le 20$ ft, K is estimated by

$$K = K_o - \frac{H_{2i}}{20}\left(K_o - K_a\right) \tag{8}$$

The horizontal force on the reinforcement at this level is thus, $F_{Hi} = A_P\,\sigma_{Hi}$ where A_P = Area of the panel. Therefore, the tensile stress $\sigma_T = F_{Hi} / A_S$, where A_S = area of the selected strip = w×t. For the reinforcement at this level to be safe against rupture $\sigma_T \le q_a$, where q_a is the allowable tensile strength of the reinforcing material.

Tensile Stress at the Connections: The horizontal force at the connections is generally assumed equal to 85% the maximum horizontal force, thus $F_{H,\,Conn} = 0.85\,F_H$. Using this force, the tensile stress at the connection is calculated by $\sigma_{T,\,Conn} = F_{H,\,Conn} / A_{reduced}$ where $A_{reduced}$ is the reduced area of the strip due to the bolt hole. This stress must be less than q_a.

Pullout of Reinforcement: The pullout capacity of the strip reinforcement at level i, P_i, is estimated as $P_i = 2\,w\,\gamma\,H_i\,L_e\,f^*$ where w = width of the reinforcement, and L_e is the equivalent length within the failure zone (Fig. 3). The apparent coefficient of friction between the soils and the reinforcement f^* is calculated by the average height of the overburden. As shown in Fig. 4(b), f^* is assumed to decrease linearly from 1.5 at z = 0 to tanϕ at z = 20 ft and remains constant thereafter. The factor of safety against pullout can be computed as $SF_{pullout} = P_i / F_{Hi}$. This safety factor must be ≥ 1.5.

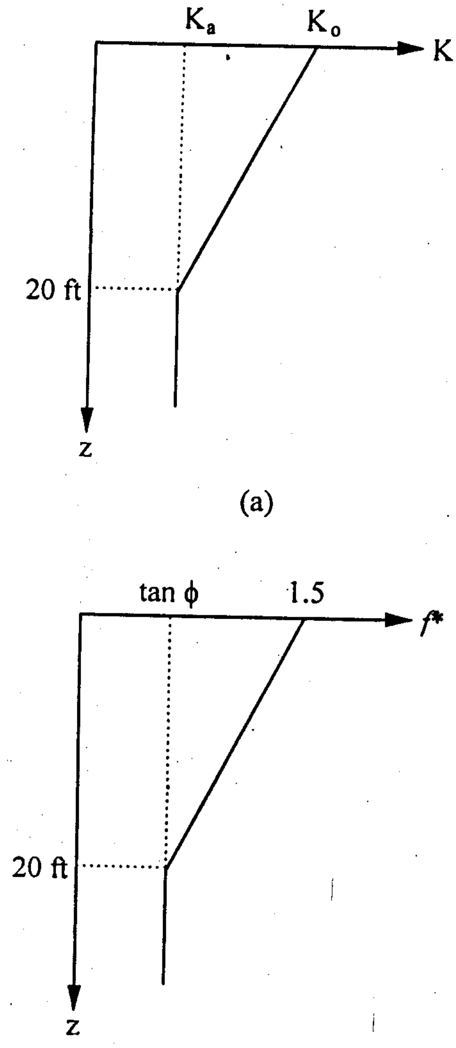


Fig. 4: Variation of (a) K and (b) f^* with Depth

Program Development: The program for the design of reinforced earth walls is written in Advanced BASIC Language. Fig. 5 shows the overall flow chart of the program. The program allows data inputs in either a data file format or directly on the screen. Fig. 6(a) shows the possible modes of data inputs and the input data required. The input data is then displayed as shown in Fig. 6(b). The program uses these input data to estimate the required length of the reinforcement. The appropriate length is sought so that the wall is safe for sliding, overturning and bearing capacity. Once this is achieved, the program proceeds to evaluate the internal stability of

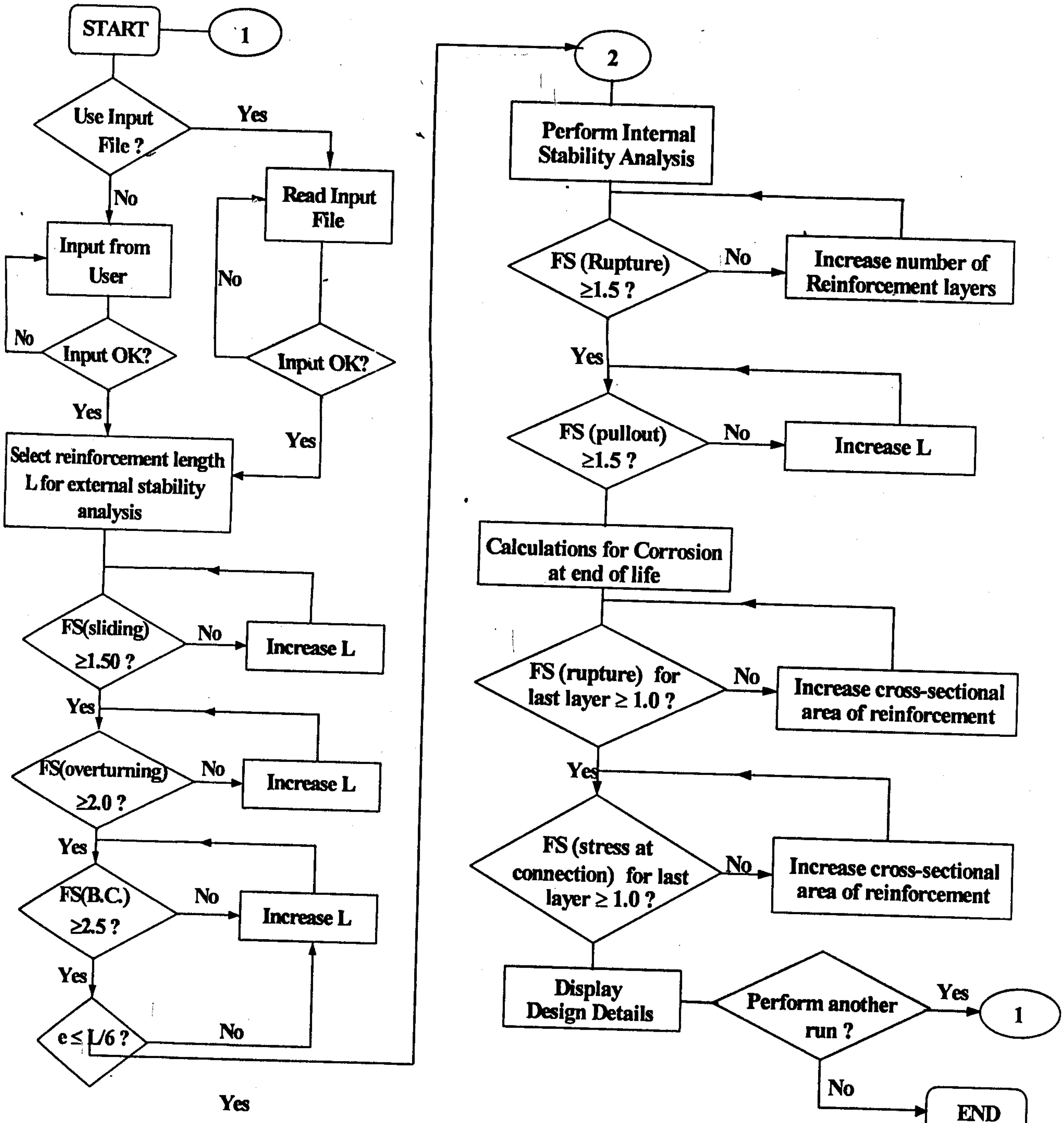
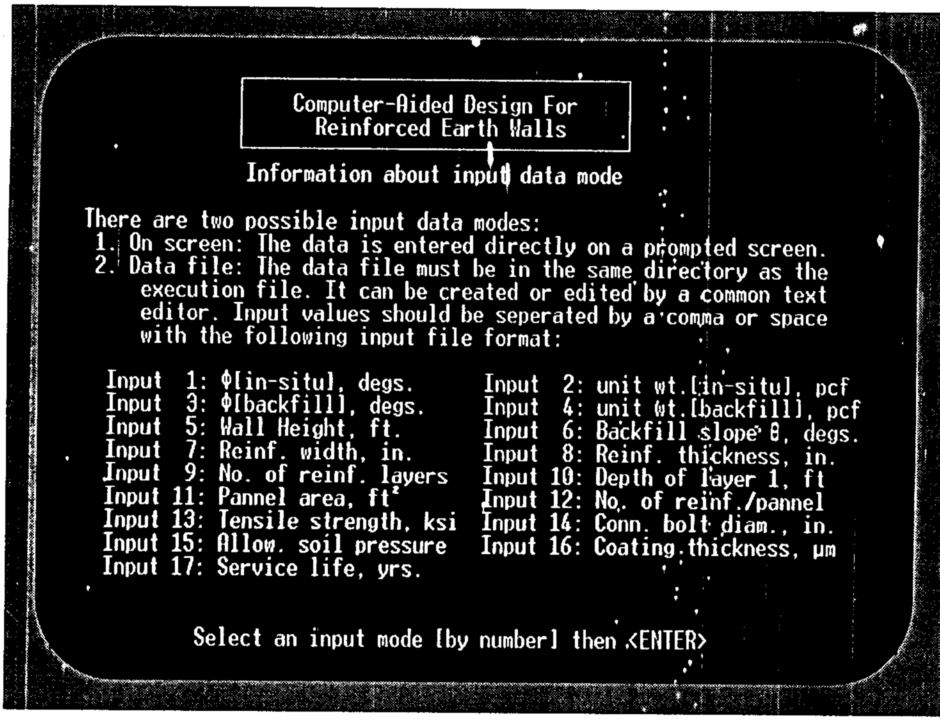
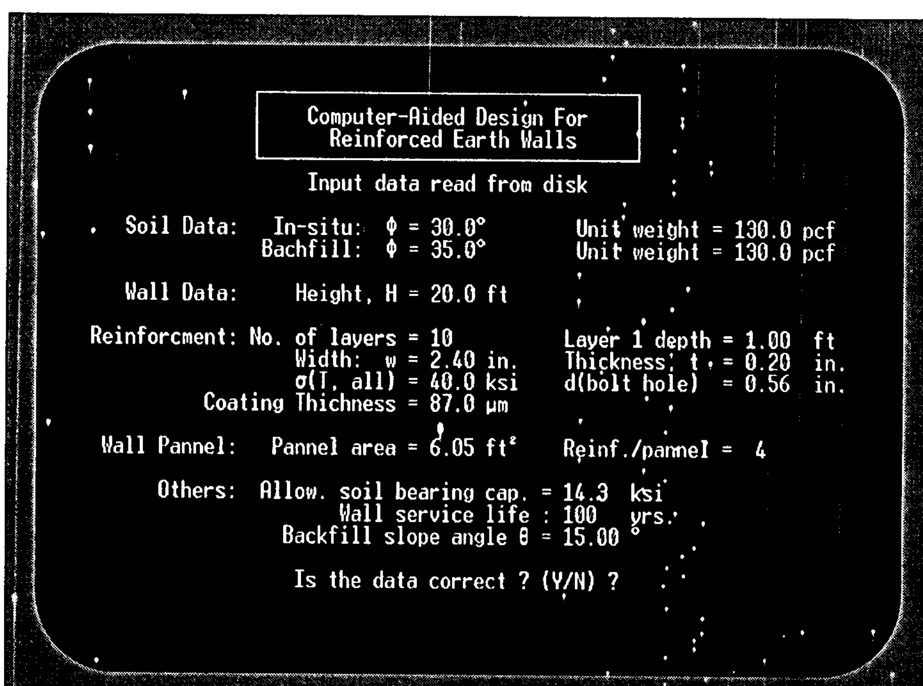


Fig. 5: Overall Flow Chart of the Reinforced Earth Walls Computer-Aided Design Program

the wall by calculating the forces and stresses. The stresses at all reinforcing layer are checked to insure no rupture and pullout of the reinforcements and no tensile failure in the reinforcements and connection. An additional check is performed to safeguard against failure due to reinforcement corrosion after a specified period of time. The calculations of the forces and stresses on each reinforcement layer for the safe wall results in the display of the information on the screen, as illustrated in Fig. 7(a). As both external and internal safety are insured, the program displays a screen depicting a summary of the final design of the safe wall as presented in Fig. 7(b).

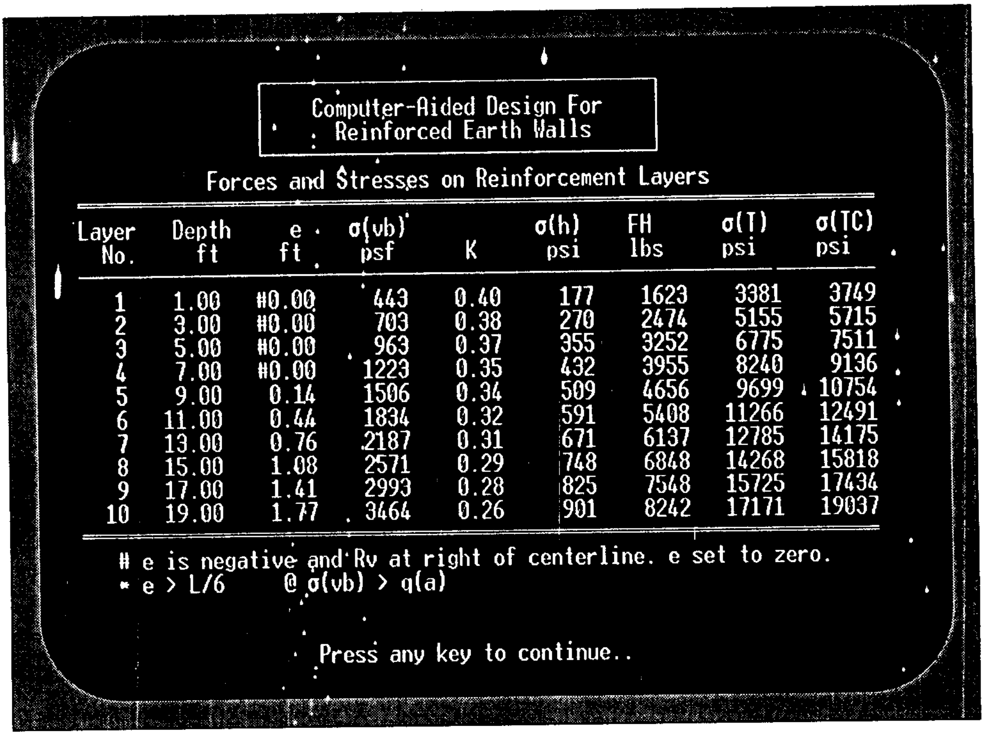


(a)



(b)

Fig. 6: Screens for Data Input



Computer-Aided Design For
Reinforced Earth Walls

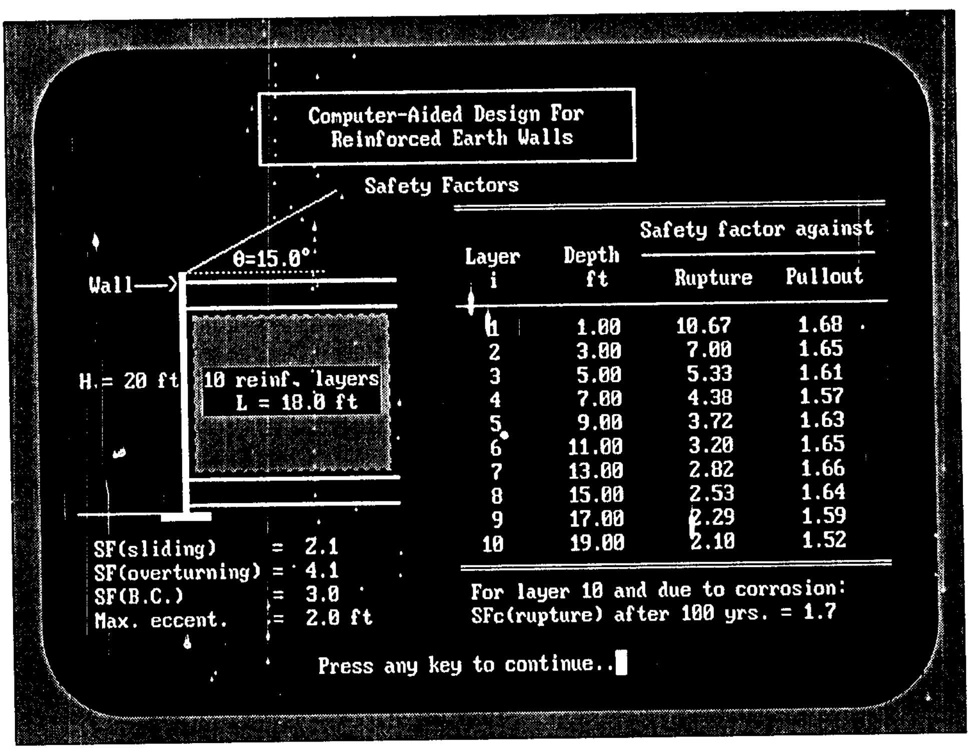
Forces and Stresses on Reinforcement Layers

Layer No.	Depth ft	e ft	σ(vb) psf	K	σ(h) psi	FH lbs	σ(T) psi	σ(TC) psi
1	1.00	#0.00	443	0.40	177	1623	3381	3749
2	3.00	#0.00	703	0.38	270	2474	5155	5715
3	5.00	#0.00	963	0.37	355	3252	6775	7511
4	7.00	#0.00	1223	0.35	432	3955	8240	9136
5	9.00	0.14	1506	0.34	509	4656	9699	10754
6	11.00	0.44	1834	0.32	591	5408	11266	12491
7	13.00	0.76	2187	0.31	671	6137	12785	14175
8	15.00	1.08	2571	0.29	748	6848	14268	15818
9	17.00	1.41	2993	0.28	825	7548	15725	17434
10	19.00	1.77	3464	0.26	901	8242	17171	19037

e is negative and Rv at right of centerline. e set to zero.
* e > L/6 @ σ(vb) > q(a)

Press any key to continue..

(a)



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Safety Factors

SF(sliding) = 2.1
SF(overturning) = 4.1
SF(B.C.) = 3.0
Max. eccent. = 2.0 ft

Layer i	Depth ft	Safety factor against Rupture	Safety factor against Pullout
1	1.00	10.67	1.68
2	3.00	7.00	1.65
3	5.00	5.33	1.61
4	7.00	4.38	1.57
5	9.00	3.72	1.63
6	11.00	3.20	1.65
7	13.00	2.82	1.66
8	15.00	2.53	1.64
9	17.00	2.29	1.59
10	19.00	2.10	1.52

For layer 10 and due to corrosion:
SFc(rupture) after 100 yrs. = 1.7

Press any key to continue..

(b)

Fig. 7: Screens for Program Output

Program Verification: To verify and validate the accuracy of the computer program, the program output for various conditions and soil properties were compared with calculations by the manual design methods. The results indicate a very good agreements between the two methods. Thus, it is anticipated that the level of confidence of the program is very high.

Conclusion

Due to the popularity of reinforced earth walls and the repetitive nature of the design method, a computer-aided design technique for such structures is a genuine essentially. With the commonality and availability of micro-computers, the potential advantages of a program for the design of such walls tailored for micro-computers, cannot be overstressed. This paper had , therefore, developed a simple and interactive program for the design and analysis of such walls. A comparison between the program outputs for various wall conditions and the solutions by the standard design method showed considerable agreement, thus, substantiating the accuracy of the program. The use of the computer-aided design technique for reinforced earth walls would surely facilitate the design procedure. Such a design work will no longer be time consuming and exhausting.

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