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An analytical approach to compute design loads of reinforced earth embankments under surface loads

Une façon analytique d'évaluer des charges de surface superficialles

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ABSTRACT: This paper presents the data from performance studies upto failure of reinforced earth wall model fully instrumented and subjected to surface area loading with varying edge distances. Complete instrumentation such as strain gauges, lateral and vertical earth pressure cells, an eighty six point light emitting diode (LED) tell tale system for sequential record of strip breakages etc. (designed, fabricated, calibrated and tested by the authors) was used to measure various values including lateral pressure on facing elements and tensile stress variation along reinforcing strips. For correlation studies, these values are compared with the corresponding values computed from classical earth pressure theories modified to simulate the test conditions. The load intensity causing first strip breakage is taken as the ultimate load on the wall and this value divided by a factor of safety 3 considered appropriate in view of the various constraints affecting field construction procedures and quality assurance, is taken as the allowable load.

RÉSUMÉ: Ce papier présente les données d'études de fonctionnement jusqu' à l'insuccès du mobèle du mur de sol renforcé, entièrement instrumenté st sou mis au chargement de surface superficielle avec des distances de bord variées. L'instrumentation entière comme extensomètres (à résistance électrique), cellules de pression des terres latérales et verticales, un système révélateur d'une diode de quatre-vingh-six points qui émet de la lumière (LED) pour le rapport séquentiel de ruptures de bandes, etc. (créée, fabriquée, calibrée et mise à l'essai par les auteurs) était employée pour mesurer des caleurs variées y compris la pression latérale sur des éléments à surfacer et des variations de contrainte de tension le long des bandes d'armature. Pour desétudes de corrélation, ces valeurs sont comparées aux valeurs correspondantes, calculées des théories classique de pression des terres, modifiées pour simuler les conditions de l'essai. L'intensité de la charge qui produit la première rupture de bandes est prise comme la charge finale sur le mur et cette valeur, divisée par un coefficient de sécurité 3, considérée juste, étant donné les contraintes variées qui affectent des procéedures de construction au chantier et la garantie de qualité, est prise comme la charge permise.

1 INTRODUCTION

Reinforced earth walls with galvanized steel strips for reinforcement and R.C.C. cruciform shaped facing panels have come to stay as a credible innovative construction technique for approach embankments of flyovers, abutments etc. Considerable research and performance studies on laboratory model and field prototypes have resulted in better analysis, design methods and construction techniques as well as specifications for materials to be used, with its attendant improved performance and quality assurance. Nevertheless, correlation studies between lateral earth pressures actually measured in tests and those obtained from classical earth pressure theories duly modified to simulate test conditions have been scarce. This paper details an attempt to modify the expressions (based upon classical theories) to evaluate lateral pressures to obtain reasonable correlation with those actually measured in laboratory tests, when the first strip breakage is observed.

2 DESCRIPTION OF THE MODEL

Figure 1 shows the assembly of the RE wall model built in a model box that fits into a self straining loading steel frame fitted with an appropriate loading mechanism and load measuring device comprising of a hydraulic jack and a proving ring each of 100 tons capacity. The model box of size 1.03 × 1.12 × 1.08 m has three sides made up of wooden planks stiffened with steel sections and the fourth side is open and kept free from the adjacent sides to facilitate fabrication of RE wall comprising of hand cut steel strips 800 × 10 × 0.137 mm for reinforcing elements provided with a hole at either end to receive a 3mm steel bolt with washers to facilitate connection to the skin element at +the facing end and LED circuit connection at either end. The horizontal and vertical spacing of these strips are 27 cm and 6 cm respectively. The skin elements (86 nos.) of teak wood, cruciform in shape and 180 × 120 × 20 mm in size are made up of two pieces 13 mm and 7 mm thick laid one over the other and nailed such that edge projections are available for necessary interlocking. The facing end of each strip is connected to the facing element at its center through an aluminium T bracket connector of size 20 × 18 × 18 mm screwed into the panel at its center. Soil used for the back fill is a medium sized sand (sw-sp) obtained from a nearby river source. The soil is compacted in layers such that the finished thickness of each layer equals the vertical spacing of strips. The strips are laid horizontally on the surface of the compacted layer and properly positioned and the next layer of soil is spread uniformly to the required thickness and compacted. This process is repeated till the model is completed. All the relevant properties of the materials used for facing elements, joints, reinforcing strips and the soil used, are determined and checked to satisfy the specifications and for use in the design. The arrangement of facing elements, and the details of instrumentation provided, common to all tests, is presented in Figure 1. Each strip is connected to the LED assembly that is provided with a bulb projecting out at the center of each skin element, which blows out when the strip breaks and thus breaks the circuit. The circuit details of the LED assembly, the actual lay out of loaded surface area and edge distances adopted for all the tests are shown in Figure 2 and in Figure 3.

3 INSTRUMENTATION USED

a) Multi-channel switching and balancing units for measurement of strain gauged bridge output simultaneously from about 60 locations.

b) 50 mm diameter stainless steel diaphragm type strain gauged earth pressure cells to record lateral pressure on skin elements.

c) 100 mm diameter brass diaphragm type pressure cells to record

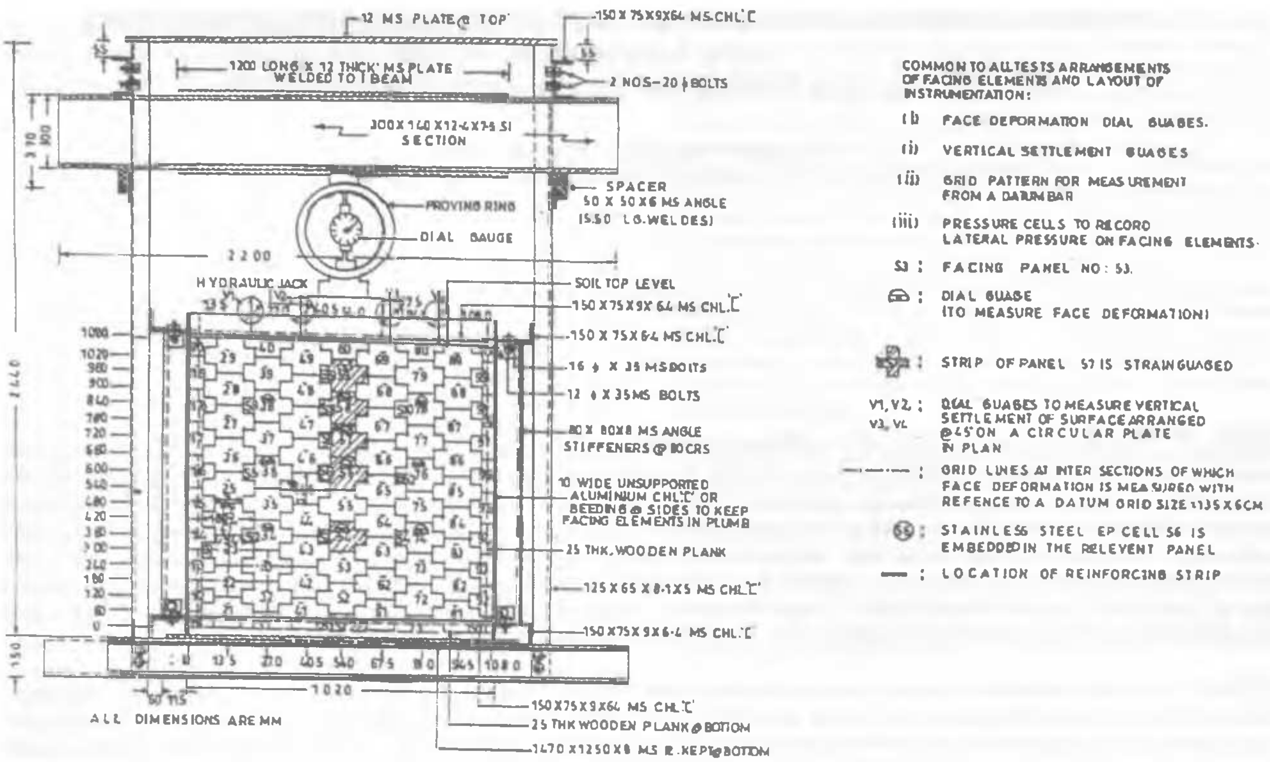
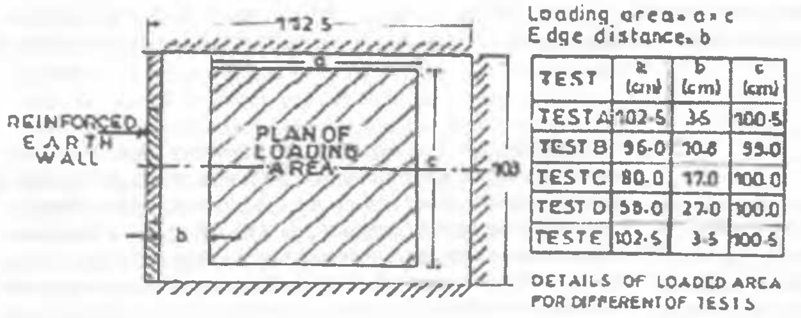


Figure 1. Elevation of loading frame and reinforced earth model wall and instrumentation details.



Loading area = a × c
Edge distance = b

TEST	a (cm)	b (cm)	c (cm)
TEST A	102.5	3.5	100.5
TEST B	96.0	10.6	99.0
TEST C	80.0	17.0	100.0
TEST D	58.0	27.0	100.0
TEST E	102.5	3.5	100.5

DETAILS OF LOADED AREA FOR DIFFERENT OF TESTS

Figure 2. Plan of surface loaded area for different tets showing edge distance from R.E. wall.

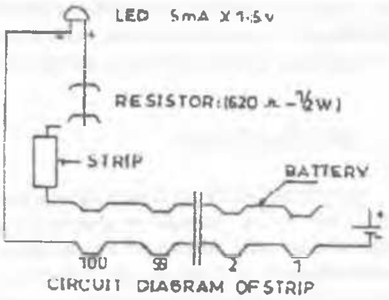


Figure 3. Layout of instrumentation LED display unit (common to all tests)

i) toe pressures at either end and center of RE wall, ii) lateral pressure along the height of one rigid vertical side of the model box, iii) vertical pressure in the compacted soil fill at three different depths vertically below the center of the loaded area.

d) Strain gauged (half bridge) reinforcing strips to record the tensile stress variation along their length. These are located at the relevant and vulnerable positions (usually along the central section of the loaded area) to obtain the peak values of various parameters.

Also, included is the apparatus to conduct pull out test on the dummy additional strips provided, equipment for calibration of pressure cells, dial gauges and datum bars to measure lateral deflection of RE wall, and dial gauges to measure surface settlement at the four corners of the loaded surface area in all the tests conducted up to failure.

4 TEST PROCEDURE

The construction of model is completed after ensuring that the instrumentation has been duly installed at each stage as planned and ensuring its satisfactory working. The plates one over the other decreasing in size from bottom to top plate for transfer of load applied are arranged over which the load application device and measuring device are properly positioned. All initial readings from the instrumentation are also recorded. The load is applied gradually in increments of 50 kN/m^2. After each load increment, all the instruments are checked, read properly and the values recorded. This is repeated till the first strip breakage occurred, as indicated by the blow out of the glowing bulb at the center of the skin element connected to the broken strip, and continued till failure, as indicated by either excessive lateral deformation of the wall leading to considerable gap between adjacent skin elements with attendant leakage of soil fill or by breaking of reinforcing strips accompanied by noise and excessive outward movement of skin elements or a possible combination of both. Later, the set up is carefully dismantled, and the sand filling is carefully removed in stages to facilitate complete and correct record of location and mode of breakage of all torn strips. Quite a few strips failed at the bolt hole connection with the facing elements. The same procedure is repeated for all tests conducted.

5 COMPUTATION OF RESULTS

5.1 Load intensity causing first strip breakage

5.11 Experimental approach:

For any test, the load intensity corresponding to the first breakage of strip(s) is obtained from the LED display board. The total

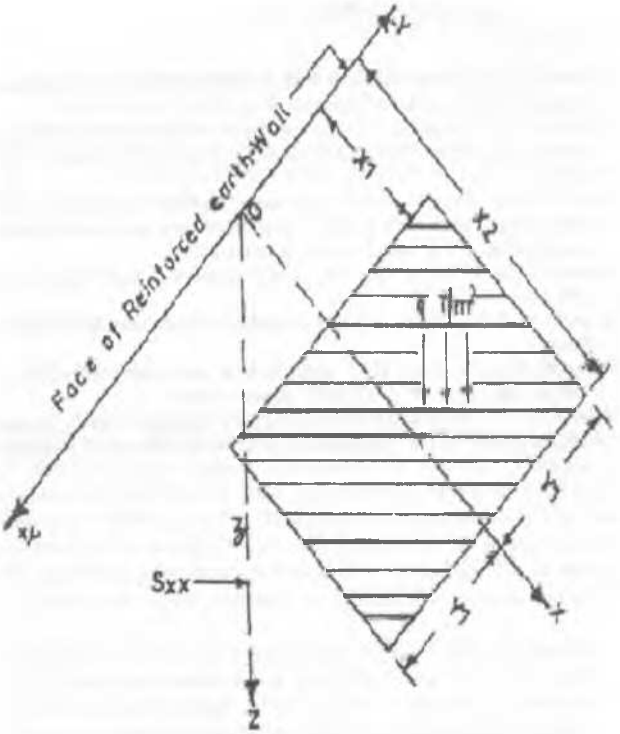


Figure 4. Boussinesq's Approach (for area loading)

load applied as indicated by the proving ring divided by the loading area gives the value.

5.12 Analytical approach

After a discreet study of the various classical theories, Modified Spangler's approach is found to give values closest to the experimental values in respect of the surface area load intensity causing the first strip breakage. The approach to derive the expression is briefly as follows. For a point load P, Boussinesq's formula for the lateral pressure s_{xx} on a flexible wall imagined to be a simple vertical plane in an elastic half space is given by

$$s_{xx} = \left(3P \cdot x^2 \cdot z\right) / \left(2\pi R^5\right) \tag{1}$$

taking Poisson's ratio μ for back fill as 0.5 and $R = (x^2 + y^2 + z^2)^{1/2}$. The Spangler's formula, a modification of Boussinesq's point load formula for a rigid retaining wall, considered by Terzaghi (1943) and Spangler (1982) etc. is given by

$$s_{xx} = 2\left(3P \cdot x^2 \cdot z\right) / \left(2\pi R^5\right) \tag{2}$$

Spangler's modified formula intuitively arrived at for computing the lateral pressure on a RE wall facing having partial rigidity is given by the expression

$$s_{xx} = \left(2 - R^*\right)\left(3P \cdot x^2 \cdot z\right) / \left(2\pi R^5\right) \tag{3}$$

where R^* is a reduction factor explained below. This equation is integrated for a rectangular surcharge load intensity q(t/m²), shown in Figure 4, and the lateral pressure on the wall facing due to superimposed area load is given by

$$s_{xx} = \left(2 - R^*\right)\left(3P \cdot x^2 \cdot z\right) / \left(2\pi R^5\right) \tag{4}$$

where

$A = \tan^{-1}\left(x_2 y_1 / z R_{x2}\right)$, $B = x_2 y_1 z / \left(x_2^2 + z^2\right) R_{x2}$,
$C = \tan^{-1}\left(x_1 y_1 / z R_{x1}\right)$, $D = x_2 y_1 z / \left(x_2^2 + z^2\right) R_{x1}$,
$R_{x1} = \left(x_1^2 + y_1^2 + z^2\right)^{1/2}$ and $R_{x2} = \left(x_2^2 + y_2^2 + z^2\right)^{1/2}$

Lateral pressure distribution on the RE wall facing elements due to an area surcharge will be maximum on the central vertical section of the loaded area. The values for each symbol used in the equations are obtained for each test conducted. The value of the reduction factor R^* is evaluated from the relation $R^* = 1 / (1 + k^*)$ where k^* is the relative stiffness factor (Relative flexural rigidity) of the facing or skin of a RE structure. For a perfectly rigid facing, $k^* \to \infty$ while for a perfectly flexible facing, $k^* \to 0$. If $k^* = 0$ then $R^* = 1$ and if $k^* = \infty$, then $R^* = 0$.

$$k^* = \frac{\left(39 - \mu_s^2\right) E_p \left\{t / \left(H/2\right)\right\}^3}{\left(12 - \mu_p^2\right)} \tag{5}$$

where μ_s and μ_p are the Poisson's ratios of the reinforced soil (assumed as 0.35) and wall facing material (taken as 0.25 for teak wood) respectively.

For steel and reinforced concrete these values are 0.3 and 0.15 respectively. E_p and E_s are the stress-strain moduli for facing material and reinforced soil. The latter is taken approximately equal to that of unreinforced back fill soil, which depends upon a number of factors such as in-situ density, rate of loading, vertical stress, confining pressure, stress history etc. This is to be determined from the slope of the tangent drawn at the relevant point on the stress strain curve obtained from triaxial compression test conducted in the laboratory on back fill sample (CD test). Alternatively this may be obtained as E_t (Tangent modulus for the backfill) as proposed by Kondener and Zelasko (1963) and modified by Duncan and Chang (1970) from the equation:

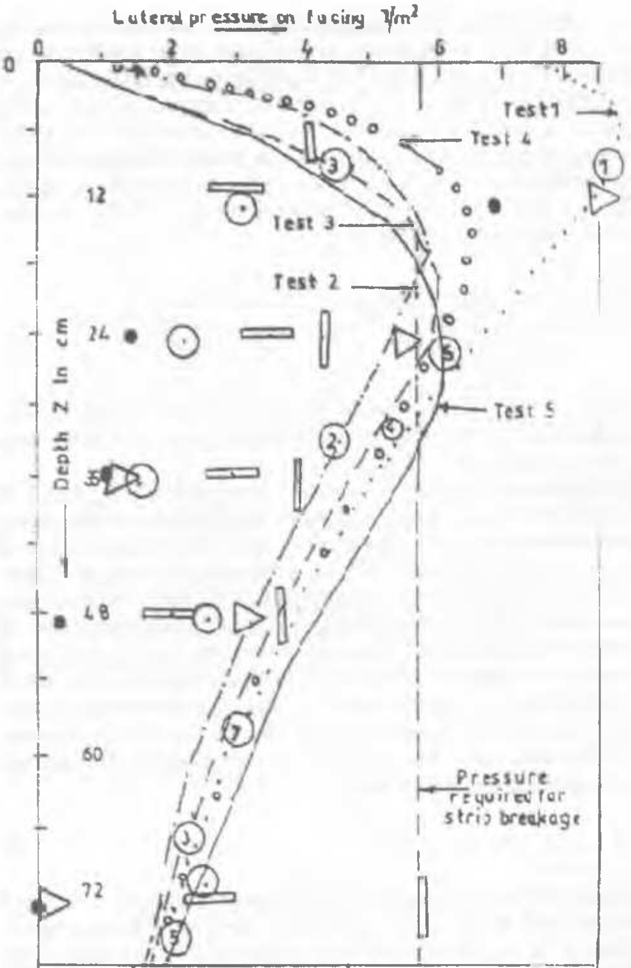
$$E_t = \{1 - M\}^2 k s_a \left(s_h / s_a\right)^n \tag{6}$$

where $M = R_f\left(1 - \sin\phi\right)\left(s_v - s_h\right) / \left(2c\cos\phi + 2s_h \sin\phi\right)$ and R_f is a failure ratio equal to $(s_v - s_h)$ at failure divided by the asymptotic value of $(s_v - s_h)$, k is a modulus number, n is an exponent determining the rate of variation of initial tangent modulus with s_h, s_a is atmospheric pressure (10.13 t/m²), c is cohesion and ϕ is angle of internal friction of the back fill. E_t is taken as zero if the value of $M \geq 1$. Values of R_f, k, n, c, and ϕ are to be determined experimentally. However, in the absence of tests the following values can be assumed in respect of a cohesionless soil fill: $R_f = 0.70$, $k = 400$, $n = 0.5$, $c = 0$ and $\phi = 36°$. The major principal stress $s_v = (s_1)$ is due to the self weight of backfill and the surface load above. The vertical stress component due to the surcharge is assumed to disperse uniformly on an area bounded by 2:1 dispersion. The lateral pressure on the RE wall facing s_{xx} can be computed as the sum of the lateral pressures caused due to compacted soil fill and the surcharge load applied on the surface.

5.13 Correlation of data and design

Figure 5 presents the correlation study between the load intensity causing first strip breakage as obtained from test data and as computed analytically based on modified Spangler's classical theory as explained above for all the five tests conducted. The analytical values are within a small bandwidth. The measured values show wide variation. This is possibly related to low values of edge distances, which could not be monitored because of limitations imposed by the model dimensions chosen. The analytical values with a factor of safety of 3, are pretty close to the test values and are on the safe side. With a minimum edge distance of one tenth of the height of RE wall the correlation has become more trust worthy. As such it is recommended that for a given RE wall either built or to be built, the allowable area load intensity that causes first strip breakage load can be computed and the allowable load intensity can be computed adopting a factor of safety of 3, subject to a minimum edge distance of 1 m or 1/10 height. The design of the reinforcing strip against tension mode of failure is

$$T_{max} = s_{xx} \cdot \Delta H \cdot \Delta S = s_{yy} \cdot b \cdot t / FS_y$$



Test No	Lateral Pressure (a)	Lateral Pressure (b)	Strip Breakage load T/m² (a)	Strip Breakage load T/m² (b)
1	......	═	12·3	18.6
2	—·—·	⊙	15·9	15·8
3	----	▷	13·4	20·0
4	oooooo	▯	15·7	16·4
5	——	●	27·6	30·0

(a) As per modified Spangler (b) Recorded

Figure 5. Lateral pressure (recorded & computed)

Against pull out mode of failure,

$$T_{max} = s_{xx} \cdot \Delta H \cdot \Delta S = s_{yy}(max.) \cdot 2b \tan\phi\, Le / FS_{\mu}$$

FS_y and FS_{μ} are factors of safety against tension and pull out modes of failure of strips, s_{xx} max., for a given load intensity q, taken as the maximum of all the values computed for different depths up to the bottom of the wall is adopted in the design.

6. CONCLUSIONS

1. The analytical approach using modified Spangler's method yields a good prediction of the intensity of surface area loading causing first strip breakage, as, seen from test data, subject to a minimum edge distance of 1 m or H/10, and a factor of safety of 3.
2. This approach tallies with the criteria for internal stability against tension failure and pull out failure of a usually adopted in RE wall design.

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