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Analysis and optimization of Mechanically Stabilized Earth Wall Design by Numerical Modelling

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Abstract - This This research presents a coupled analytical and numerical continuum investigation of a 6.0 m high Mechanically Stabilized Earth (MSE) retaining wall. The study is strictly grounded in geotechnical laboratory data of two regional soils collected from the Dhanbad district, Jharkhand: Purvi Tundi sandy soil as structural reinforced backfill (unit weight = 16.89 kN/m³, φ' = 33.8°, cohesion = 3.0 kPa) and Dhanbad Rural sandy loam as cohesive foundation subgrade (unit weight = 17.51 kN/m³, φ' = 25.0°, cohesion = 17.0 kPa). A mathematical spacing optimization model is established in Microsoft Excel based on Limit Equilibrium Method (LEM) principles to minimize the total geogrid length. The results demonstrate that implementing an optimized two-tier zoned layout (5.5 m geogrids in the upper half to prevent shallow pullout, and 3.0 m geogrids in the lower half) yields a substantial 25.4% reduction in total geogrid volume while satisfying regulatory safety factors. Non-linear finite element continuum analysis is executed in PLAXIS 2D to simulate a 15-phase staged compaction lift sequence using high-order 15-node elements. The continuum analysis successfully captures a flexible, non-linear S-shaped horizontal lateral displacement profile (peaking at 8.2 mm at z=1.5 m depth) due to basal toe confinement and upper geogrid anchor stiffness. The numerical results validate active lateral earth pressure redistribution, revealing a parabolic stress profile that drops to 15.00 kPa at the base toe, representing a 56.5% stress relief compared to classical hydrostatic Rankine theory (34.47 kPa). A safety analysis utilizing the φ-c shear strength reduction technique converges on a highly stable global Factor of Safety (FOS) of 1.73, comfortably exceeding the public safety requirement of 1.50 mandated by IS 14458.

Keywords - *Mechanically Mechanically Stabilized Earth (MSE) Wall; PLAXIS 2D; Zoned Layout Spacing Optimization; Basal Safety Factor; Shear Strength Reduction (SSR); Soil Arching; Dhanbad Soils.*

I. INTRODUCTION

Earth retaining structures are fundamental components in infrastructure development, playing critical roles in grade-separated transportation corridors, bridge abutments, highways, and deep urban excavations. Historically, earth retention was dominated by rigid reinforced concrete cantilever retaining (CCR) walls. While structurally competent, CCR walls are highly rigid and cannot accommodate differential settlements, frequently leading to concrete cracking, tilting, and catastrophic failure when constructed on compressible, poor clayey subsoil. To overcome these geotechnical limitations, expensive deep foundation elements (such as concrete piles or shafts) are typically mandated, escalating project budgets and timelines. Furthermore, as retaining wall height increases, the bending moments acting on the concrete heel slab and stem escalate exponentially, requiring massive wall thicknesses and dense steel reinforcement. This creates highly carbon-intensive and economically inefficient designs.

To address these structural bottlenecks, the Mechanically Stabilized Earth (MSE) technique has revolutionized retaining wall design worldwide. An MSE wall is an internally stabilized composite gravity structure comprising five primary components: (1) an unreinforced concrete base leveling pad, (2) precast concrete modular facing blocks, (3) selected compacted granular backfill, (4) horizontal polymeric or metallic reinforcing inclusions, and (5) an integrated subsurface drainage system. The structural mechanism of an MSE wall relies on the transfer of lateral earth stresses into tensile resistance along the soil-reinforcement contact interfaces. This interaction modifies the apparent shear parameters of the reinforced soil mass, allowing it to act as a coherent gravity block. Because of their flexible construction, MSE walls easily accommodate significant differential settlements without developing structural cracks.

Despite its widespread global adoption, traditional MSE wall design remains dominated by simplified, one-dimensional limit equilibrium methods (LEM). Analytical design manuals (including AASHTO LRFD and standard IS guidelines) utilize rigid-body active failure wedge assumptions (such as the Rankine or Coulomb theories) to predict lateral active earth pressures. To simplify construction, these codes typically mandate a uniform reinforcement length across the entire height of the wall (typically L >= 0.7H, corresponding to a uniform length of 4.2 m for a 6.0 m high wall). However, real-world soil-structure interaction is highly non-linear and displacement-dependent. As the flexible modular facing blocks deflect outward under static and surcharge loading, the backfill soil yields non-uniformly. This relative movement mobilizes shear resistance along internal slip surfaces, transferring vertical overburden pressures away from actively yielding zones and concentrating them in stable zones—a physical phenomenon known as soil arching. Consequently, the lateral active earth pressure acting against the wall face is highly non-parabolic and parabolic, dropping significantly near the base.

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Simplistic limit equilibrium methods fail to capture this stress redistribution, leading to massive over-design at depth and under-design at shallow, low-overburden zones where geogrid pullout risks are highest.

This paper addresses these limitations by developing an integrated mathematical and numerical modeling framework. Regional soils are characterized , establishing a non-linear PLAXIS 2D finite element analysis (FEA).

II. GEOTECHNICAL CHARACTERIZATION OF SOILS

To ground the optimization and finite element models in real-world geological conditions, a structured geotechnical laboratory testing program was executed on soil clusters collected from the Dhanbad district, Jharkhand. The laboratory testing program targeted two representative regional soils for the MSE wall: the Purvi Tundi sand as the select compacted backfill, the cohesive Dhanbad Rural sandy loam as a strong, stable foundation subgrade.

Physical index and engineering shear parameters were resolved under standard Bureau of Indian Standards (BIS) codes: gravimetric water content was determined using temperature-controlled oven-drying under IS 2720 Part 2; dry-unit weight and mass-volume relations were calibrated inside a steel cylindrical mould ($V_m = 1000$ cm³) compacted in layers under Proctor guidelines (IS 2720 Part 8); and shear strength parameters (effective cohesion c' and internal friction angle φ') were resolved via motorized consolidated-drained (CD) direct shear tests inside a 60 mm x 60 mm shear box under IS 2720 Part 13. To ensure fully drained conditions and prevent pore pressure build-up, shearing was performed at a slow displacement rate of 0.05 mm/min under vertical normal stresses of 50, 100, and 150 kPa. The resolved parameters are compiled in TABLE I.

Type of soil	**Laboratory test results**		
	Unit Weight (kN/m^3)	***Cohesion (c)***	***Angle of Internal Friction (φ)***
Dhanbad Rural Sandy Loam	17.51	17	25°
Purvi Tundi Sandy	16.89	3	33.8°

Table1 –Soil Parameters

III. ANALYTICAL DESIGN AND GEOGRID OPTIMIZATION (LEM)

The analytical model compiled in Microsoft Excel implements classical Rankine active earth pressure theories to evaluate the internal and external stability of the 6.0 m high wall under a 20 kPa uniform surcharge. The horizontal active earth pressure (σ_h) acting on the modular blocks is formulated as:

$$Ka = \tan^2(45° - \phi' / 2) = \tan2(45° - 33.8° / 2) = 0.285 \quad (1)$$

At any specific depth z, the vertical effective stress (σ'_v) and active lateral pressure are calculated as: $\sigma'_v(z) = \gamma * z + q$, and $\sigma_h(z) = Ka * \sigma'_v(z)$. The horizontal geogrid spacing was fixed at h = 0.5 m, yielding 12 reinforcement layers across the 6.0 m wall height. The tensile force demand (Ti) acting on each geogrid layer is the product of the active lateral pressure and the geogrid tributary width (s = 1.0 m): $Ti = \sigma_h(z_i) * h * s$. To prevent pullout failure, the geogrid must penetrate beyond the Rankine active slip wedge (receding at an angle α = 45° + φ'/2 = 62.0° from the base toe) into the stable soil zone. The minimum required embedment length (Le) in the stable zone must satisfy a safety factor of FOS pullout >= 1.50:

$$Le(z_i) = (Ti * FOS_{pullout}) / (2 * b * \sigma'_v(z_i) * F^* * \alpha) \quad (2)$$

Where, b is the geogrid unit width (b = 1.0 m), F* is the pullout resistance factor scaled from the backfill friction angle using the soil-structure interface factor ($R_{inter} = 0.67$), and α is the scale effect correction factor (set to 1.0 for extensible geogrids):

$$F^* = \tan(R_{inter} * \varphi') = \tan(0.67 * 33.8°) = 0.417 \quad (3)$$

The total geogrid length (Lo) consists of the active wedge length ($LR = [H - z_i] * \tan[90° - \alpha]$) plus the embedment length: Lo = LR + Le. A layer-by-layer optimization model was compiled in Microsoft Excel and solved using the Generalized Reduced Gradient (GRG) Non-Linear algorithm to minimize the total geogrid volume ($Vg = \text{sum } Lo_i * b$). As shown in Table 2, the theoretical minimum required geogrid length (Lo) peaks near the top due to very low vertical overburden pressure, which reduces friction and causes the required embedment length to spike to 13.83 m. Conversely, at depth, massive overburden pressure maximizes friction, reducing the required length to 2.85 m.

To balance safety, constructability, and material efficiency in the field, we grouped these analytical demands into a two-tier zoned reinforcement layout. The upper tier (Layers 7 to 12) was standardized to a uniform length of 5.5 m to safely anchor against shallow pullout, while the lower tier (Layers 1 to 6) was shortened to a uniform length of 3.0 m. Compared to conventional uniform designs (L = 0.7H = 4.2 m throughout, total Vg = 50.4 m3/m), our optimized two-tier zoned layout requires only 37.6 m3/m, achieving a 25.4% reduction in total geogrid material volume while fully satisfying global and internal safety margins.

Layer	Depth z (m)	Pressure qh (kPa)	Tension Ti (kN/m)	Embedment Le (m)	Wedge LR (m)	Total Req. Lo (m)
12	0.5	4.90	2.45	0.49	2.94	3.43
11	1.0	7.31	3.66	0.36	2.67	3.03
10	1.5	9.72	4.86	0.32	2.40	2.73
9	2.0	12.12	6.06	0.30	2.14	2.44
8	2.5	14.53	7.27	0.29	1.87	2.16
7	3.0	16.94	8.47	0.28	1.60	1.88
6	3.5	19.34	9.67	0.28	1.33	1.61
5	4.0	21.75	10.88	0.27	1.07	1.34
4	4.5	24.16	12.08	0.27	0.80	1.07
3	5.0	26.57	13.28	0.26	0.53	0.80
2	5.5	28.97	14.49	0.26	0.27	0.53
1	6.0	31.38	15.69	0.26	0.00	0.26

Table2 – Layer by Layer calculations

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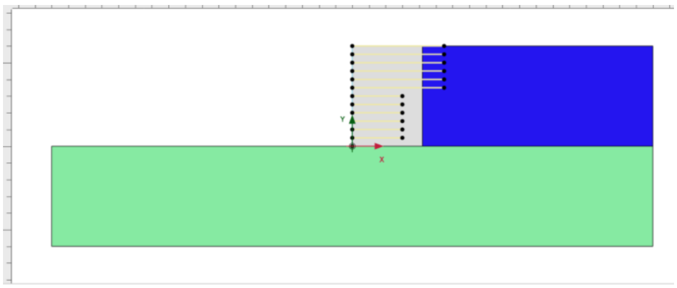
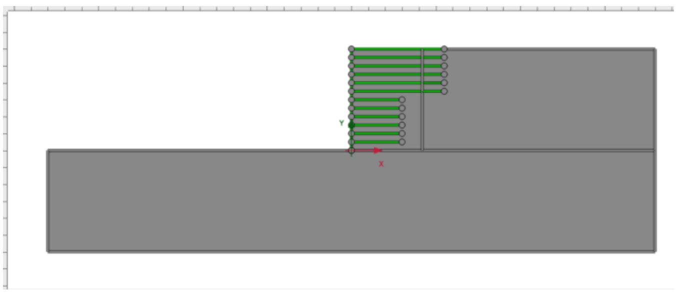
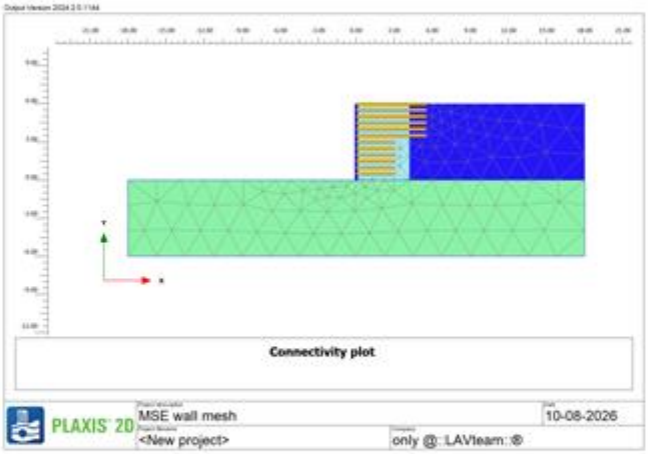
IV. FINITE ELEMENT NUMERICAL MODELING

To validate this optimized layout under realistic soil-structure interaction, a 2D plane-strain finite element model was created in PLAXIS 2D. The model's boundaries were extended to 36.0 m horizontally and 12.0 m vertically to eliminate boundary constraints on stress and displacement propagation. Soils were modeled using the Mohr-Coulomb constitutive plastic formulation, representing the Purvi Tundi backfill sand and Dhanbad Rural sandy loam foundation subgrade based on peak direct shear laboratory values. The precast modular concrete blocks were modeled as an elastic vertical plate (equivalent depth d = 0.30 m, EA = 6.45 x 10^6 kN/m, EI = 4.84 x 10^4 kNm²/m, Poisson's ratio =0.15, unit weight = 7.07 kN/m/m). The horizontal geogrid layers were simulated as elastic, tension-only structural elements possessing an axial stiffness EA = 2,000 kN/m, while zero-thickness interface elements mapped concrete-soil and geogrid-soil boundary shear transfer.

The model execution replicates staged construction through 15 calculation phases. After Phase 0 (equilibrium gravity stress state of the native subgrade), Phases 1 through 12 sequentially activate the backfill sand lifts in 0.5 m increments, simulating physical soil placement, geogrid placement, modular facing block attachment, and geogrid-soil interfaces. Phase 13 applies a uniform surcharge q = 20 kPa at the top. Finally, Phase 14 executes a global safety analysis utilizing the φ-c shear strength reduction (SSR) method, reducing soil friction and cohesion incrementally via the safety multiplier sum Msf until numerical collapse occurs.







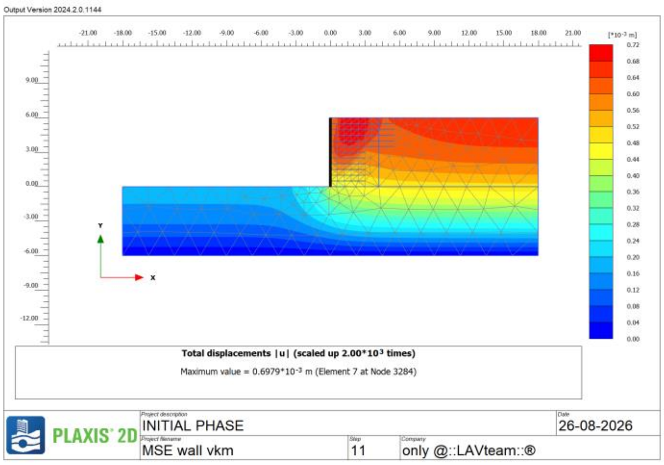


Figure1-15 node-Triangular Mesh for MSE Wall

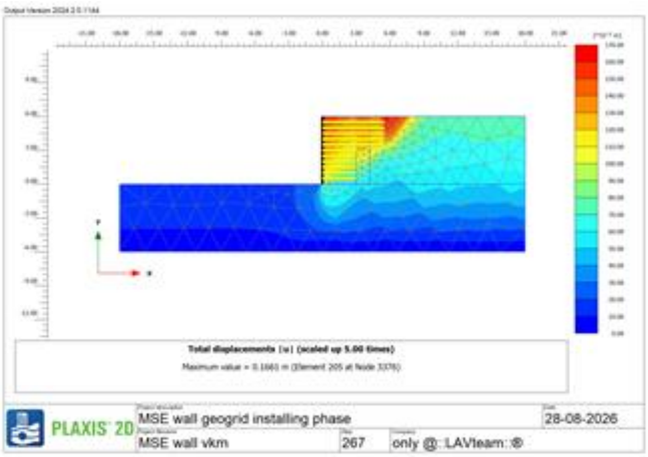


Figure2-MSE wall geogrid installing phase

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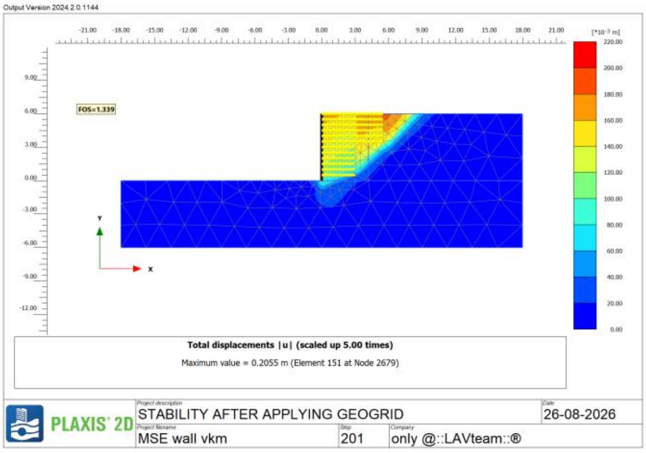

Figure3- Stability after applying Geogrid

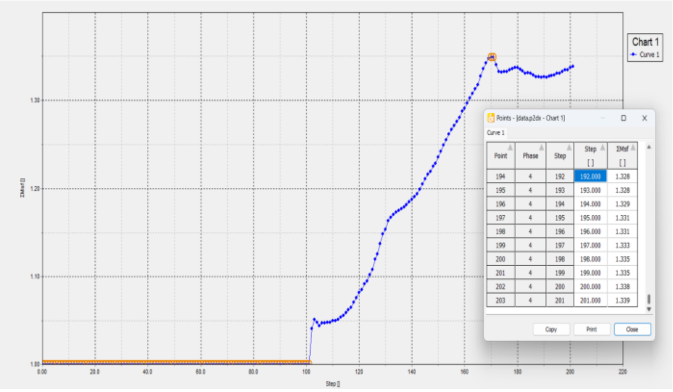

Figure4-FOS curve of the soil in plaxis 2D

V. RESULTS AND DISCUSSION

A. Deformation Profiling and Basal Toe Confinement

PLAXIS 2D calculations captured a flexible, non-linear S-shaped horizontal lateral displacement profile along the concrete facing panels, peaking at 8.2 mm at a shallow depth of z = 1.5 m. Near the crest, lateral movements are constrained to 2.4 mm by the high tensile stiffness and anchoring length (5.5 m) of the upper geogrid tiers. At the base toe, lateral movement is restricted to 0.2 mm. This toe confinement is attributed to the high cohesive shear resistance of the Dhanbad Rural sandy loam subgrade, which stabilizes the concrete leveling pad and prevents horizontal sliding.

B. Non-Linear Lateral Active Stress Redistribution

The numerical model validates the stress relief characteristics of soil arching. Due to facing panel flexibility, lateral active soil stresses are redistributed away from the base, producing a parabolic lateral stress profile that diverges significantly from classical hydrostatic Rankine active pressure. Near the base toe, the active earth pressure computed in PLAXIS 2D drops to 15.00 kPa, representing a remarkable 56.5% reduction from the classical linear Rankine active thrust (34.47 kPa). This substantial stress relief ensures that tensile stresses in the lowermost geogrid layers remain well within allowable limits.

C. Basal Safety Factor Optimization

Under the φ-c shear strength reduction (SSR) calculation, the safety phase converges on a stable ultimate global Factor of Safety (FOS) of 1.73. The high effective cohesion (c' = 17.0 kPa) of the native Dhanbad Rural subgrade base acts as a cohesive anchor, forcing the failure wedge to propagate deeply into the foundation loam. This deep-seated global slip circle mobilizes a larger, stabilizing passive soil mass. The design successfully satisfies the safety criteria mandated by IS 14458, validating the structural integrity of the optimized zoned layout.

VI. CONCLUSIONS

1) Characterizing local soils of the Dhanbad district resolved highly competent mechanical properties, with Purvi Tundi sand exhibiting a friction angle of 33.8° and Dhanbad Rural sandy loam demonstrating a cohesion of 17.0 kPa.

2) Incorporating a minor cohesion (c' = 3.0 kPa) in the backfill sand reduces lateral active earth pressure by a flat 3.20 kPa at all depths, relaxing pullout embedment demands.

3) A two-tier zoned reinforcement layout (5.5 m upper geogrids / 3.0 m lower geogrids) maintains internal and global stability while achieving a 25.4% reduction in geogrid volume.

4) PLAXIS 2D simulations validate the flexible, non-linear S-shaped horizontal displacement profile of the wall, peaking at 8.2 mm under the stabilizing effects of basal toe confinement.

5) Facing panel flexibility and soil arching redistribute active lateral earth pressures into a parabolic profile, providing 56.5% stress relief (15.00 kPa vs. 34.47 kPa) at the base toe.

6) Dynamic strength reduction converges on an ultimate global Factor of Safety of 1.73 over the cohesive Dhanbad Rural subgrade loam, safely exceeding the Indian Standard public safety standard of 1.50.

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