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Earth Pressures of Soils Partially Replaced with Building Derived Materials for Narrow Backfill Condition

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Abstract. Spaces behind retaining walls are often limited to a narrow width when they are built close to existing structures in urban areas or near rock faces in hilly terrains. Conventional earth pressure theories such as Coulomb or Rankine's theory assumes that the backfill is sufficiently wide to allow full development of the failure plane. These theories tend to over-estimate the lateral earth pressures for narrow backfills. In the present study, a laboratory scale model retaining wall is designed to investigate the effect of narrow backfill width on lateral pressures under at-rest earth pressure conditions. The present study proposes a sustainable and eco-friendly usage of Building Derived Materials (BDM) mixed with locally available red soil (R) and sand (S) as a backfill for these retaining walls.The BDM content is varied from 0 – 30% by weight of soil. Results of the tests demonstrate that the failure surfaces are limited by the width of narrow backfills. Large scale tests are generally expensive and needs added labor cost that makes it difficult to carry out a wide range of parametric studies. In this regard, numerical analysis serves as a cost-effective measure that helps in better understanding of the experimental results. In the present study, the cantilever retaining wall is modeled using commercially available finite element software PLAXIS 2D. The force - based analysis is carried out by incorporating Hardening Soil (HS) model. A series of consolidated undrained triaxial tests are conducted on soil-BDM blends in order to obtain Duncan Chang's hyperbolic parameters. The soil parameters obtained from hyperbolic modeling is used for modeling the soil in Hardening Soil model in Plaxis. The finite element results seem to be in a fairly good agreement with the experimental observations and the trend is also satisfactory for both R-BDM and S-BDM.

Keywords: Building Derived Materials; Narrow Backfill; Finite Element Analysis, Hyperbolic Modeling

1 Introduction

Soil or water at different elevations is retained by structures like cantilever sheet piles, anchored sheet piles, reinforced cantilever walls. The backfill soil is crucial portion and earth pressures induced in backfill are shear stresses which disturb the stability and performance of retaining wall and backfill as whole. It is very difficult to interpret the earth pressures of soil when the retaining wall is constructed near rockfaces and slopes which offers narrow width for backfill. For retaining walls with limited backfill space, the coefficient of active earth pressures decreases with ratio of height of wall and width of backfill [1]. Classical earthpressure theories of Coulomb and Rankine assume that the slipsurface of the backfill soil is linear planar and develops across the heel of theretaining wall with an inclination angle of (45°+φ/2) from the horizontal. Whenthe interface frictionangle between the backfill soil and the back of retaining wall is less, this assumption is found to yield satisfactory results[2]. Many analytical solutions assume that failure in narrow backfills are planar and occurs in segmental pattern [3].The shape of pressure profiles is non – linear and not a triangular distribution in case limited backfill widths; one reason for non – linear distribution of lateral earth pressures is arching of soils [4].The pressure distribution mainly depends on wall – soil interaction, angle of internal friction and aspect ratio of backfill.

In general, the failure surfaces are designed based on the assumption that the backfill extends to a sufficient distance from the wall to allow thefailure plane to fully develop across the heel of the retaining wall and into the backfill soil behind the wall. This assumption is found to be valid most of the time when retaining walls are built. However,retaining walls at times must be built adjacent to an existing stable wall to widen existinghighways or near the foundations of existing buildings in urban areas [4] orconstructed near rigid rock faces in mountainous regions [5], causing the space of backfill to be constrained and limited to a narrow distance from the wall.If the backfill aspect ratio (B/H) is less than 0.55, traditional theories like Coulomb or Rankine cannot estimate lateral earth pressures with the desired accuracy [6]. An analytical solutionbased on trapezoidal thrust failure wedge was proposed by researchers, which assume linear planar slip surface [7]. Planar and bilinear slip surfaces were assumed in limit equilibrium analysis on mechanically stabilized earth retaining walls with narrow geosynthetic-reinforced backfill soil [8, 9]. Nonlinear slip surfaces are observed by some researchers [5, 10] to be formed in narrow backfill.

The past literature indicates that very few analytical and experimental studies are available on retaining walls with narrow backfills. To the best of author's knowledge, no studies are available on laboratory model scale studies of earth pressures of backfill soil replaced with construction and demolition wastes. The present study proposes a sustainable and eco-friendly usage of Building Derived Materials (BDM)mixed with locally available red soil (R) and sand (S) as a backfill for these retaining walls.The BDM content is varied from 0 – 30% by weight of soil. Results of the tests demonstrate that the failure surfaces are limited by the width of narrow backfills. The cantilever retaining wall is also modeled using commercially available finite element software PLAXIS 2D. The force - based analysis is carried out by incorporating Hardening Soil (HS) model. A series of consolidated undrained triaxial tests are conducted on soil-BDM blends in order to obtain Duncan Chang's hyperbolic parameters. The soil parameters obtained from hyperbolic modeling is used for modeling the soil in Hardening Soil model in Plaxis. The analysis carried out on retaining walls are explained in subsequent sections.

2 Materials and Methodology

2.1 Soil

Two different types of soils are used in the present study. The first type of soil is red soil (R), collected from Medchal district in the state of Telangana, India. This is the main type of soil available in Hyderabad and surrounding areas. The soil used in the present study is found to be fine-textured. It shows a quick reaction to dilatancy test. The soil is classified as Silty Sand (SM) following Unified Soil Classification System (USCS). A plasticity index value of 7 signifies that the soil contains less clayey particles. Also, the soil is found to be almost free from swelling. Wet sieve analysis of red soil is carried out according to IS: 2720 (Part 4) – 1985. The grain size distribution curve of red soil is provided in Figure1. From Figure 1, it can be observed that value of C_u is less than 5 and that of $C_c$is 0.11 and the red soil is gap graded.

The sand (S), used in the present study, is collected from west Godavari river basin near Telangana state of India. The sand is classified as poorly graded sand (SP) according to USCS. A constant relative density of 40% is maintained by rainfall pouring method to achieve medium dense condition. It has a maximum dry unit weight of 18.43 kN/m^3, as obtained through vibratory table method. The minimum dry unit weight is 17.24 kN/m^3 obtained by pouring in its loosest state. From grain size distribution curve (Figure 1), it is observed that C_u and $C_c$of sand are 2.5 and 0.9 respectively, indicating a poorly graded soil. The sand particles, as observed through stereomicroscopic images, are mostly angular in shape, with smaller percentages of rounded and sub-rounded particles.

2.2 Building Derived Material (BDM)

The BDM is collected from two local construction and demolitionsites near Shameerpet area in Telangana, India. The construction and demolition wastes consist of concrete, brick, ceramic tiles, glass, wood, and plastic; concrete and brick. According to Bhattacharya et al. (2013), CDW consists of 65% concrete, 25% brick, 5% wood and 5% miscellaneous materials like metals and plastic. The concrete and brick component of this CDW is separated manually and used as BDM for this study. The collected BDM is crushed with the help of a mechanical jaw crusher to less than 10 mm,10mm – 30mm and 30mm – 50mm. The grain size distributions of each of these sizes are analyzed before and after compaction. It is observed that more than half of larger sized particles tend to get crushed under the action of load. Hence, particles in the range of 2.36 to 10 mm are utilized in the present study.Grain size distribution curves of locally available soils blended with BDM are presented in figure1.

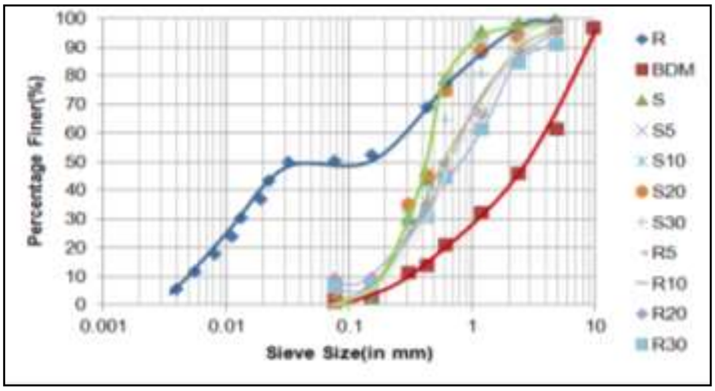


Fig. 1. Particle Size Distribution of soils blended with Building Derived Materials

2.3 Model retaining wall apparatus

The laboratory scale model retaining wall apparatus is designed in a tank of length 1.2 m and height of 0.9m. The front side of tank is fitted with acrylic sheet of 25mm and three sides are built with mild steel(Figure 2). The retaining wall is instrumented with earth pressure sensors to capture pressure distribution and an inclinometer to monitor the rotations. This setup represents plane strain boundary conditions with rigid, non – yielding wall of dry backfill. The wall is arranged at 0.65m position to create narrow backfill condition; when L/D is less than 0.4, it resembles a narrow backfill conditions [10]. Rotation is enabled with hinged attachment provided at the bottom base of tank. Active and passive conditions are created by pulling the wall from backfill or pushing the wall into the backfill with jack attached to it. The hydraulic jack of capacity 150 kN is arranged at 0.75 m height to hold the plate in up – right position and also to rotate the plate.To ensure uniform load distribution on to plate element, a bar element is fastened on non –

backfilled side in contact with hydraulic jack. Three earth pressure cells of embedded type are arranged on the backfill side to assess pressures at three different conditions of rotation.Diameter of EPC is 200 mm with 7 mm thickness with compressible fluid in pressure pad. The accuracy of sensor is (+) or (-) 0.5% and can measure up to 500 kPa. A LVDT is arranged on the non – backfill side to calculate displacements of wall from mean position. A rough interface is created by sticking emery paper on backfill side. The interface angle (δ) is calculated by shear box tests and found out to be 13.2° for R – BDM and 13.6° for S – BDM blends respectively. This interface angle also depends on grit size of emery paper and type of soil utilized for the study.

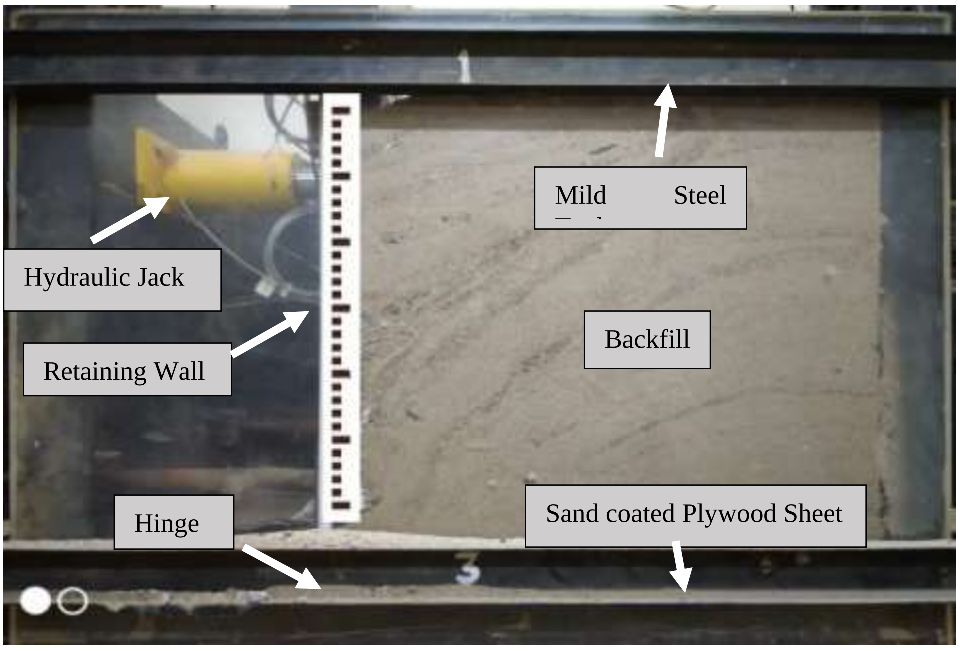


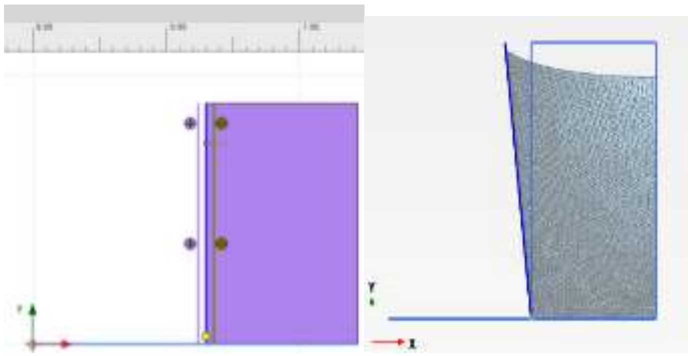
Fig.2. Model Retaining Wall Test Apparatus

2.4 Numerical Modelling

A numerical modelling is carried out in PLAXIS 2D to validate the experimental results using plane strain conditions. 15 noded triangular elements called as cubic triangle are selected with very fine meshing(Figure 3). The material properties of numerical model are tabulated in Table 1. Hardening Soil model is used as constitutive relation to analyze stress – strain response of soil elements. Hardening soil is formulated based on Duncan – Chang hyperbolic postulates [11], which is utilized for soils in elastoplastic and perfectly plastic states as backfill soils will achieve plastic state when subjected to rotations.

Table 1. Input Parameters of Numerical Model

Element	Values
1) Plate element	
EA (kN/m)	1.25×10^{7}
EI (kN m^2/m)	1.15×10^{5}
Weight (w) (kN/m/m)	8.2
Poisson's ratio (υ)	0.15
2) Hinge element	Free to rotate at top
3) Interface element	
$R_{\text{inter (R – BDM)}}$	0.7
$R_{\text{inter (S – BDM)}}$	0.8
Interface Strength	Rigid



(a) (b)

Fig.3. (a)FEM model of retaining wall (b) Deformed Mesh in K_a case

3 Results and Discussions

Variation of maximum dry unit and optimum moisture content with BDM content is presented in Figures 4a and b respectively. It is observed that the unit weight of soil composite is increasing proportionally with increase in BDM content. This is because void spaces in soil mass are occupied by BDM particles till 20% of replacement. After 20% replacement, unit weight is decreased due to increment in void spaces. When soil mass is replaced by 30% BDM, major quantity of load is taken by BDM particles which leads to improper densities. Optimum values of dry unit weight and optimum moisture content of sand are reported as 19 kN/m^3 and 8.5%, while that of red soil are 18 kN/m^3 and 7.5% respectively on addition of 20% of BDM. Sand – BDM (S – BDM) content exhibited more unit weight values than red soil – BDM (R- BDM). Addition of coarse (BDM) particles increases the gradation parameters and increases the unit weight upon compaction. This in turn, increases the shear strength till optimum content of BDM is replaced.

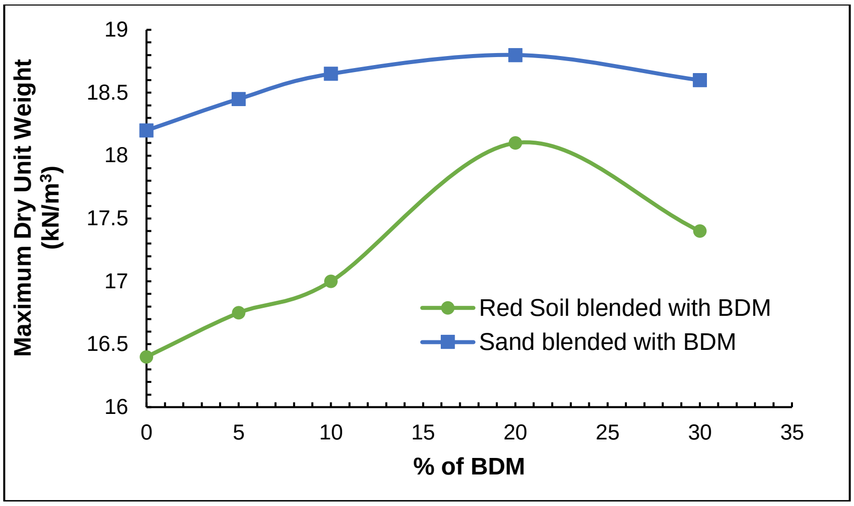


Fig. 4a. Variation of MDD with % of BDM

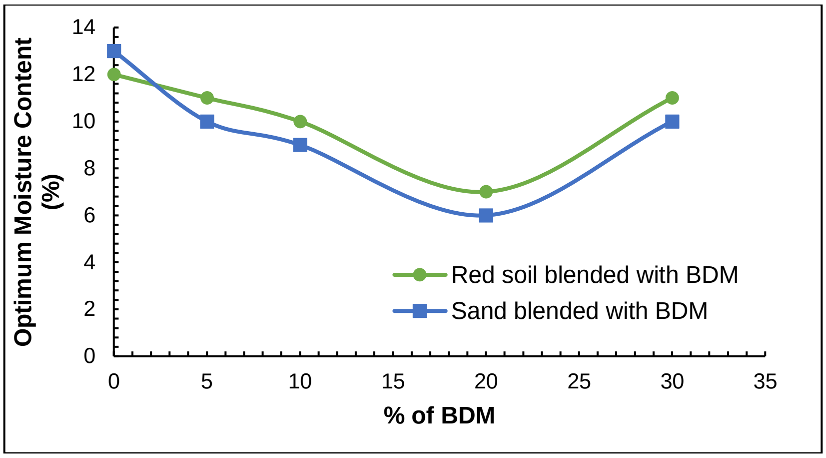


Fig. 4b. Variation of OMC with % of BDM

Figures 5a, b and c present the variation of at-rest, active and passive earth pressures along the height of the wall respectively. From figure 5a, it is observed that observations from experimental investigations are discrete and following a non – continuous distribution with wall height. Jaky's theory and readings recorded from numerical methods are indicating triangular distribution. At – rest earth pressures are dependent on unit weight of soil and its angle of internal friction. In K_0 case, Jaky's theory underpredicted the earth pressures for R – BDM and S – BDM blends. At – rest earth pressures are range of 2.5 – 10 kPa for both blends while numerical method predicted a triangular distribution with pressures ranging from 2.4 to 7.5 kPa.

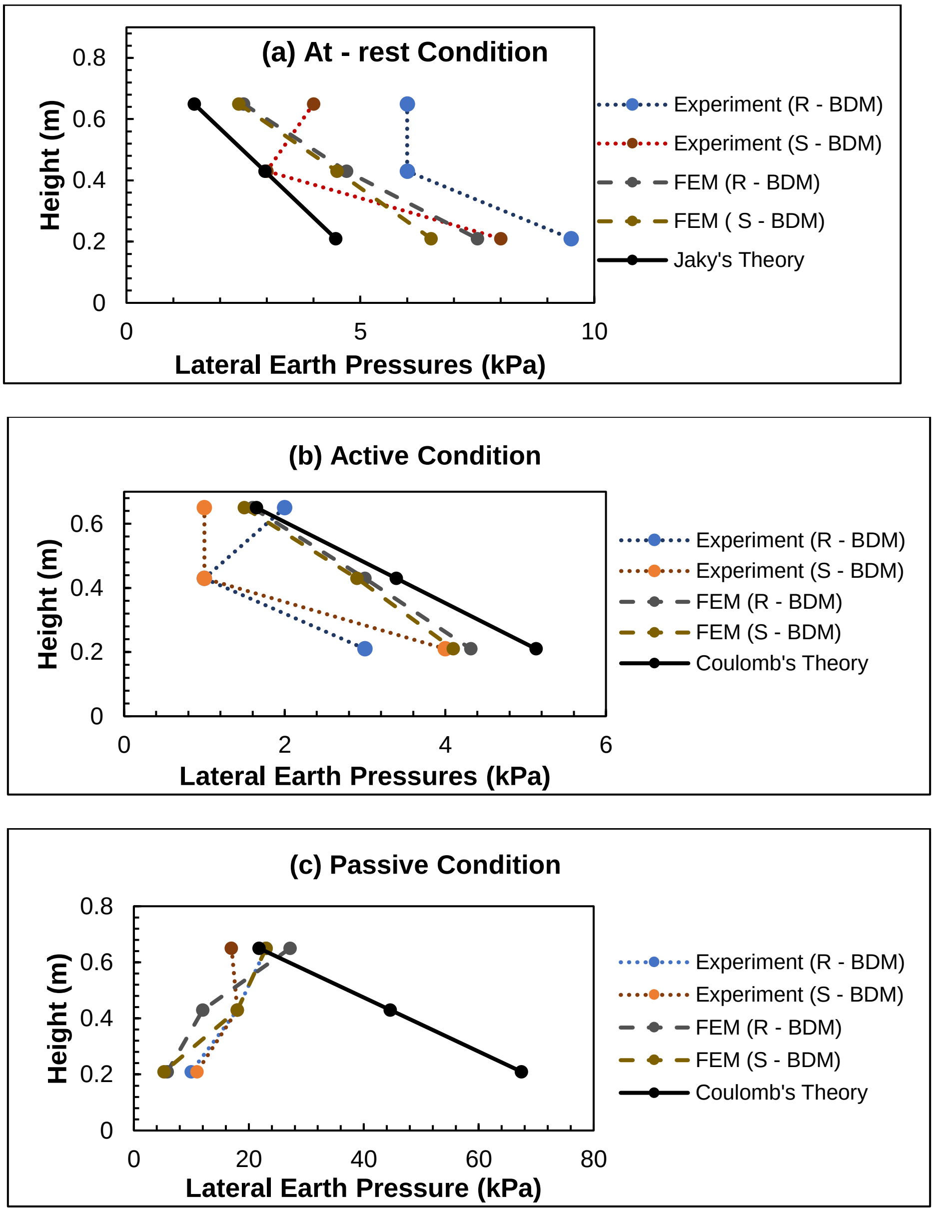


Fig. 5. Variation of (a) at-rest, (b) active and (c) passive earth pressures with height of wall

Active case (K_a) which is created from rotating the wall away from backfill, is important in designing a retaining structure. Active earth pressures are lower in terms of magnitude when compared with at – rest case. Experimental observations are compared with Coulomb's theory equation as the wall – soil interaction is rough. Non – continuous nature is observed in experimental outcomes, deviation is observed in middle sensor points. This is due to loss of contact between soil and sensor as wall is made to rotate away from backfill. Active earth pressures are dependent of unit weight of soil, shear strength offered by backfill material and interaction. Coulomb's theory has over predicted the pressure readings subtended by experiment and numerical outcomes. Numerical and Theoretical values are following a triangular distribution with pressures increasing linearly with wall height. Experimental readings are in range of 1 – 4 kPa for both blends in active case.

Passive case, which is created by rotating the wall into backfill is crucial in stability calculations of retaining structures. Passive earth pressures are resisting forces offered by backfill soil against rotation of wall are presented in figure 7. Greater magnitude of pressures is observed for backfills which possess higher unit weights. From the figure, it is observed that reverse trend is notedin contrast with traditional theories. Passive pressures are in magnitude of 5 – 27 kPa with greater magnitudes of pressures in the upper part of wall. This is due to the fact thatthe top of the wall is rotated into the backfill with the help of hydraulic jack.

Figures 6and 7 present the comparison between experimental and numerical results of both R – BDM and S – BDM blends.Values from numerical modeling under predicted experimental results in K_0 case, whereas in K_a, K_p case numerical modeling values over predicted experimental outcomes. Error percentages in all three cases for two blends are less than 20%. This study suggests that hardening soil model based on hyperbolic theory can be useful in assessment of earth pressures at field conditions.

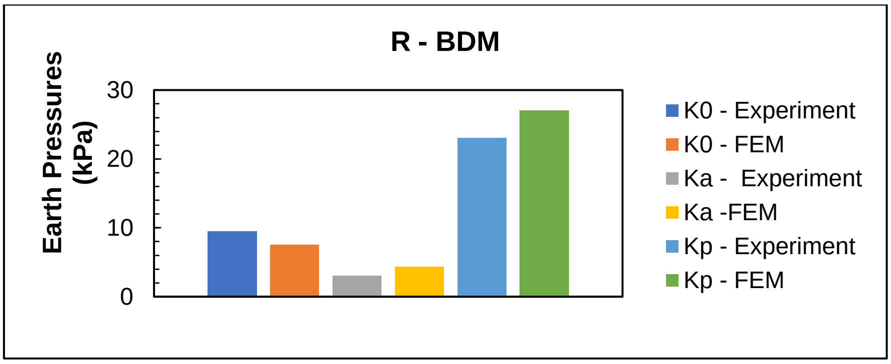


Fig. 6. Comparison between experimental and numerical results for R – BDM blend

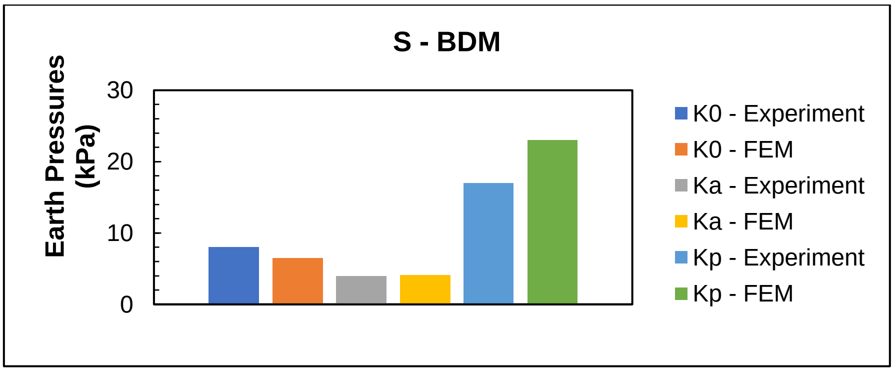


Fig. 7. Comparison between experimental and numerical results for S – BDM blend

In any case of rotation, slip surfaces cannot be developed fully in backfill at narrow backfill position. Hence, physical modelling followed by numerical analysis can present the critical parameters and failure surfaces with appropriate outputs.

The present study is limited to dry backfill condition with zero surcharge loading. Only 3 EPCs are used to measure the lateral earth pressures. More number of EPCs will give a better understanding of the distribution of earth pressures. Care is taken during the experiment so as the model steel retaining wall does not bend under the action of lateral pressure. The soil is considered to be homogenous and compacted at a relative density of 40%. However, in some cases it is difficult to maintain a constant relative density. The presence of BDM particles in backfill sand renders it to be non – homogenous. In the finite element model, plane strain condition is assumed. Ideally 2 more EPCs needs to be placed on the transverse side of the wall in order to check whether the earth pressures are coming out to be same in the transverse direction. However, in addition to the measurements of lateral pressure at various locations, a visual observation of the backfill movement from the top further confirms that the boundary effects were negligible. It is observed that the backfill soil moves and settles uniformly in the transverse direction, indicating that the potential boundary effects due to both the transverse dimension and side wall frictions are negligible. As a result, the retaining wall model can be categorized as a plane-strain model and backfill movements can be observed and characterized from its sides. This observation is consistent with the studies of Yang and Tang [10].

4 Conclusions

Precise estimation of earth pressures acting on retaining walls mainly depends on slip surface developed in backfill. The present study proposes aneco – friendly and sustainable usage of Building Derived Materials (BDM) admixed with locally available soils as backfill materials. A narrow backfill condition is considered when the ratio between the backfill width and height of the retaining wall falls below 0.4 and the slip surface intersects with the back wall. The following conclusions can be drawn based on the findings of the present study

1. The maximum dry density is attainedits peak value on mixing 20% BDM with soil.
2. In passive case, greater values of earth pressure areobserved near the top of the wall and decreased with depth, in contrast to the classical earth pressure theories as the wall is rotated about its base.
3. In active case, earth pressures from experimental investigations exhibited lesser values than the earth pressures calculated from Coulomb's Equation; Jaky's theory underpredicted the experimental results in K_0 case.
4. An increase in backfill width decreases the rotation of wall, thus reducing the probability of rotational failure. Hence narrow backfills are more prone to rotational failure.
5. Hardening soil model based on Duncan – Chang hyperbolic relation can capture the stresses and displacements induced in backfill soil for R – BDM and S – BDM blends.

6. The numerical results suggest a good agreement with that of experimental results, for all three positions of the wall, the variations in at-rest, active and passive earth pressure values are in the range of 20-25% as seen from the plots.

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