Study of Narrow Reinforced Earth Wall – A Review

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Abstract. In cases where the space available for the Reinforced Earth (RE) walls is less than required, "narrowed reinforced earth walls" are usually preferred for construction which placed adjacent to the existing stable slopes/walls. The behavior of such narrow RE walls differs from traditional RE walls and differences include a magnitude of earth pressure, failure modes, and distribution of tension along with the reinforcement which is required to be understood as these wall systems have contrasting behavior to conventional RE wall. Also, by considering actual characteristics of narrow RE walls, the design of a narrow RE wall can be improvised further to give economical design solutions. Hence, this paper provides reviews of research papers that have been done so far with regards to the narrow RE wall. That research work covers an extensive scope of the area, including centrifugal modeling study, numerical modeling, and field-scale tests on the performance of a narrow RE wall. Literature study revealed that there exists a significant reduction in lateral earth pressure adjacent to shoring wall at greater depth due to arching effect and wall aspect ratio and friction characteristics of boundary walls plays a governing role on the reduction of lateral earth pressure behind narrow RE wall. Moreover, critical failure plane was found to be bilinear having an inclination angle less than Rankine's failure plane which passes through partially from reinforced fill zone and partially from an interface between narrow RE wall and existing stable wall face.

Keywords: Limited backfill width, Lateral earth pressure, Narrow RE wall, Arching theory, Shoring wall

1 Introduction

Retaining wall is encountered in various fields of civil engineering such as bridge abutments, highway constructions, hydraulic structures, and mining protection. In conventional reinforced earth walls, the minimum required reinforcement length according to design guidelines should be 0.7H where H is equal to the height of the wall. However, due to limited space available and additional cost of unshored excavation leads to construction of RE walls in limited space and in front of existing stable wall/slopes. These walls usually preferred in urban areas to increase existing highway width or in mountain terrain to construct highway adjacent to rock stratum. These walls are referred to as the Narrow RE wall. According to Federal Highway Administration (FHwA) MSE-wall design guidelines, Narrow RE walls are referred as RE walls having an aspect ratio L/H (ratio of wall width L to wall height H) of less than 0.7 and placed in front of existing stable wall/slopes [1]. Figure 1 shows the difference between a conventional segmental retaining wall and one with shorter reinforcement length placed in front of an existing wall or rock stratum.

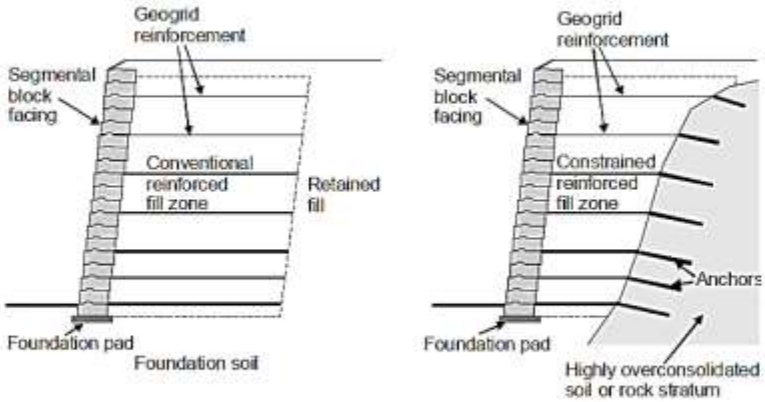

Fig. 1. Difference between (a) conventional segmental RE wall (b) Narrow segmental RE wall

As shown in Fig. 1(b), narrow RE wall has shorter reinforcement length (less than 0.7H) and existing wall or rock stratum instead of longer reinforcement length and retained fill compared to conventional RE wall. Also, the existing wall was stabilized by means of anchors, also known as shoring wall or man-made wall, which was designed to avoid additional lateral pressure from the shoring wall (as seen Fig. 1).

2 Significance of the study

The objective of this paper is to review research work, which was done so far in RE wall with constrained width to understand actual characteristics of it. As seen in Fig. 1(b), due to limited length available, the full development of the Rankine failure surface may not be possible to develop which develops in conventional RE wall. Also existing wall act as a boundary constraint, which leads to study the behavior of this wall by different researchers, including numerical modeling studies, laboratory studies, and full-scale testing on narrow RE wall. Main focus was given to the distribution of lateral earth pressure along with the depth of narrow RE wall with varying aspect ratio. Laboratory studies include centrifugal modeling studies for at rest and active earth pressure conditions with or without surcharge loading. Numerical analysis includes modeling of narrow RE walls in Finite Element Method (FEM) based software such as PLAXIS, FLAC, RESSA or limit equilibrium approach was used to understand stress distribution at upper layers of reinforcement. Based on that, some authors suggested analytical solutions to estimate lateral earth pressure behind the narrow RE wall, which is related to Arching Theory. This concept was introduced by Janssen's (1895) for analysis of horizontal pressure exerted by silo structures [3].

3 Literature Review

3.1 Arching Theory

Janssen (1895) conducted model tests on a small scale model of silo structure to analyze pressure exerted by silos in which he found that pressure applied on the bottom of the silo was less than the weight of the granular fill (such as corn or wheat) within the silo. Based on this study, he assumed that the weight of granular fill was transmitted to side walls and developed an equation to predict the horizontal pressure behind the silo structure. This theory is widely known as "Arching Theory" or "Janssen's Arching Theory"[3]. Spangler and Handy (1984) applied this concept for the analysis of the RE wall with limited backfill width. Arching theory states that due to two vertical boundaries, as the soil settles due to its self -weight and overburden pressure, simultaneously, sidewalls provide a vertical shear load due to friction that resists the settlement of soil. This vertical shear load (or side friction) leads to redistribution of stresses within granular fill, and thus lateral earth pressure reduces adjacent to the vertical stable wall face. This phenomenon has become known as the arching effect.

3.2 Physical modeling studies on narrow RE wall

Frydman and Keissar (1987) performed centrifuge model tests to study the lateral earth pressure distribution behind a narrow retaining wall placed adjacent to a rock face. All tests were performed on models with an aspect ratio from 0.1 to 1.1. In each test, the model was spun up at an acceleration of 43.7 g in the middle of the wall without any wall movement. Then the retaining wall moved outward the soil until the soil reached its limit state. The earth pressure cells were set at 1/3rd and 2/3rd of the wall height. Backfill properties include; particle size in the range of 0.10-0.30 mm, density between 14.0 - 16.4 kN/m3, angle of internal friction (φ) equal to 36° and angles of interface friction (δ) between cohesionless sand and wooden blocks was 20° - 25° and the sand was placed at a relative density of 70%. Outcomes show for at-rest earth pressure condition; arching theory gives a better prediction of lateral earth pressure while for active earth pressure conditions due to progressive failure within soil mass adjacent to facing a wall, φ value decreases and suggested to use decreased φ value for estimation of lateral earth pressure.

Take, and Valsangkar (2001) conducted centrifugal model tests on the narrow backfill width of an unyielded fascia retaining wall. Height of the model test was kept as 140 mm corresponding to 5 m high prototype wall, and backfill width was changed as 184, 75, 38 and 15 mm corresponding to aspect ratio in the range of 0.1 to 0.7. Tests were performed for variable aspect ratio, friction characteristics of boundary walls and relative density of sandy soil. Dry cohesionless sand was used as backfill material which was classified as poorly graded sand (S.P.) with little or no fines having maximum and minimum dry densities were 16.2 and 13.4 kN/m^3, respectively. Six boundary pressure cells were used, and all experiments were performed at an acceleration of 35.7 g. Results demonstrated a reduction in lateral earth pressure behind fascia retaining wall with narrow backfill width and has good agreement with

Janssen's arching theory for the case of vertical boundaries of similar frictional characteristics while in case of different frictional characteristics, the average interface friction angle should be chosen for a reasonable estimate of the earth pressure distribution.

Similarly, to investigate the effect of aspect ratio, reinforcement spacing, and reinforcement strength on narrow reinforced soil walls, Woodruff (2003) performed model tests on a centrifugal testing machine. For all test conditions, aspect ratios (L/H) varied from 0.17 to 0.9 keeping wall height equals to 230 mm, and the wall facing batter was 11: 1 (H: V). Monterey No. 30 sand was used as a backfill material, and non-woven geotextiles were used as a reinforcement. A series of triaxial compression tests were performed at a relative density of 70% to determine the internal friction angle of Monterey no 30 sand which comes out to be 36.7 º corresponding to unit weight of 16.05 kN/m^3. Woodruff (2003) observed that aspect ratio had a dominant effect on the failure mode of reinforced earth wall. Based on his laboratory work, he discovered that when aspect ratio (L/H) was between 0.25 and 0.6, the wall fails in a compound mode in which failure surface partially passed through the reinforced fill zone and partially through the edge between the reinforced fill zone and existing stable wall having a flatter inclination angle than that predicted by the Rankine theory.

Lee et al. (2010) also performed centrifuge tests on narrowed MSE walls under surcharge loading to study internal and external deformations of Shored Mechanically Stabilized Earth (SMSE) wall systems which were an extensive work of Woodruff (2003). For all test conditions, an aluminum box with inside dimensions of 0.24 m wide by 0.63 m long by 0.72 m high was used, and footing settlement, lateral deformation and internal displacement of reinforcements were measured using telltales, LVDT's and potentiometers. The main focus was given on the identification of the location of maximum strain on SMSE wall models that are subjected to surcharge loading and found out that the maximum tensile stress line in the reinforcement layers was different from that predicted by Rankine theory for conventional MSE walls. For the upper portion of the wall, the line coincides with the centerline beneath the footing, and for the lower portion of the wall, it was close to the Rankine failure plane. Also, it suggested the use of high tensile geosynthetics reinforcements to avoid a tensile rupture in the upper layers.

Xu et al. (2016) performed centrifugal modeling tests to check the effect of interface connection on a narrow MSE wall having an inside bench under surcharge loading condition. Both walls were connected by mechanical connection in which rear end of the reinforcements coming from narrow RE wall was wrapped around a horizontal long steel rod and then fixed onto hooks which were pre-installed into the shoring wall. In all test conditions, yellow sand, which has a C_u of 1.69 and a C_c of 1.05 and D_{60}, approximately 0.37 mm was used. The backfill was compacted to relative compaction of 70%, and the peak friction angle was 36°. Reinforcement used in this study was an of polyamides fabric screen net having a tensile strength of 0.32 kN/m in the cross-machine direction at a tensile strain of 47%. Wooden blocks were used to form an existing stable face. Results depict that the provision of connection helps control the wall deformation, decrease the earth pressure difference around the inside bench, and improve stability of the system. Moreover, the critical failure plane of the narrowed MSE wall for a connected system was bilinear and tangent to/touching the inside bench, which is different from conventional MSE walls.

3.3 Field Scale Tests on narrow RE wall

An investigation on the performance of a field-scale SMSE wall constructed at the Turner Fairbank Highway Research Center (TFHRC) in Washington, D.C., USA was conducted by Morrison et al. [9]. To examine two hypotheses: (a) reduction in lateral earth pressures due to the presence of a rigid back slope or shoring wall; (b) a limited advantage of the connection of reinforcements to shoring wall. The test wall had a height of 5.5m having an aspect ratio of 0.25H at the base and increasing to 0.4H at the top. A total of 12 layers of Tensar® UX1500 geogrid reinforcement was used and a facing consisting of a combination of welded wire mesh and a woven geotextile wrap. The wall backfill was mortar sand compacted with lift thicknesses of 0.46m. The MSE wall and shoring wall components were constructed with a facing batter of 1H: 24V and 1H: 6V, respectively. The test wall was instrumented with reinforcement strain gages, pressure cells, LVDTs, potentiometers, and inclinometers for the evaluation of wall face deflection, reinforcement strain, and earth pressure as well as footing settlement. Results show that lateral earth pressure values at the back of MSE mass adjacent to the shoring wall are less than or equal to theoretical zero surcharge Rankine active earth pressures that support the hypothesis. The secondary hypothesis suggesting that providing interface connection has limited benefit as full-scale test walls exhibited similar behavior for connected and unconnected wall systems, especially with regard to deformation and strains in the geogrids, supporting this hypothesis.

In the same way, Luo et al. (2018) also executed full-scale tests on a high narrow mechanically stabilized highway in Hubei Province. This full-scale test includes measurements of tensile strain in geogrids, vertical and lateral earth pressure, lateral displacement, and settlement for a period of two years after the end of construction. The tested section was having a height of 37m with a facing batter of 1H: 2V and length of reinforcement varying from 12-24 m with top six-layer went into existing backfill soil to help control differential settlement. Backfill used in construction was exhumed soil from tunnel excavation having friction angle 36° and uniaxial HDPE geogrids having an ultimate tensile strength of 90 kN/m was used as reinforcement layers which were connected to anchor bolts at rear ends to enhance pullout resistance capacity. The front face of a narrow RE wall was created by wrapped-around facing combined with seed-nutriment-soil sacks. Results indicated that vertical earth pressure was found to be smaller than theoretical earth pressure around rock benches and the tensile strain distribution around rock benches was shirking and relaxing while strain was higher on the top of rock bench.

3.4 Numerical modeling studies on narrow RE wall

Leshchinsky et al. (2004) performed limit equilibrium analysis using the computer program ReSSA 2.0, where Bishop's method was used to estimate horizontal earth pressure behind a narrow reinforced earth wall. He also introduced a procedure to calculate long term design strength of the reinforcement in which single layer of reinforcement was first placed at 1/3rd height of wall and then reinforcement force, T was kept changing until factor of safety comes to 1 which was clearly indication of limit equilibrium state and T was equal to lateral earth pressure due to backfill but opposite in direction. Results of limit equilibrium analysis were compared with another finite difference program called FLAC 4.0 and experimental results conducted by Frydman and Keissar (1987). Based on that, Leshchinsky et al. (2004) developed design charts to calculate earth pressure coefficients behind limited backfill space having a different aspect ratio (B/H) and facing a batter of shoring wall; 1:m (H: V). Results indicated that as aspect ratio decreases, lateral earth pressure also decreases.

Kniss et al. (2007) conducted finite element analysis to investigate the earth pressures behind nonyielding narrow RE walls, those with very stiff having inextensible reinforcement. Results from finite element analysis were compared with arching theory and centrifugal tests performed behind narrow walls with different aspect ratios. Results indicated that a reduction in lateral earth pressure takes place as an aspect ratio of narrow RE wall decreases. The lateral earth pressures calculated from finite element analysis were also compared with those in the FHWA criteria for MSE walls. The results show that for walls with the typical aspect ratio (L/H) of 0.70 showed good agreement with the recommended values for walls with stiff, inextensible reinforcement however for walls with lower aspect ratios (less than 0.6), lower lateral earth pressures were shown behind RE walls.

A series of limit equilibrium analysis was performed by Yang et al. (2011) to locate critical failure surfaces within narrow GRS walls having extensible reinforcements.. Results from limit equilibrium analysis were compared with experimental results conducted on a narrow GRS wall and found to be in good agreement with it. Results indicated that the location of the critical failure plane played an important role in the determination of embedment length to calculate the factor of safety against pullout failure. Inclination angle decreases as the wall aspect ratio decreases having a bilinear failure plane for lower aspect ratio, which passes tangentially at the interface between narrow GRS wall and existing stable wall. Subsequently, a series of parametric studies were performed to understand the behavior and mechanics of the narrow GRS wall and results showed that the effect of simulating pullout resistance along the reinforcement was vital and should be included in the analysis to capture the location of the critical failure surface. The parametric study on the effect of input tensile forces revealed that a wall designed using the tensile force suggested by FHWA design guidelines [9] was stable and the calculated failure surface was in the safe side of design for pullout resistance.

Tavakolian and Sankey (2011) studied the effect of interface connection by numerical analysis under a finite difference program called FLAC behind narrow shored reinforced earth walls (SREW). In this paper, three different cases were considered; in the first case, reinforcement was curtailed down nearshoring wall; in the second case, direct connection of reinforcement with anchors were created, and mechanical connection from new RE wall to existing stable wall and in the third case, sandwich connection was preferred where two reinforcements were overlapped to each other by creating friction connection between narrow RE wall and existing wall. Horizontal deformation and tensile forces induced in reinforcements were calculated for all three cases, and results demonstrated that sandwich connection substantially reduces horizontal stress and resulting tensile force in primary reinforcements and helps control the deformation of combined wall systems.

4 Concluding Remarks

Reinforced Earth wall having an aspect ratio less than 0.7H which was placed in front of existing stable wall/ rock stratum is referred to as Narrow Reinforced Earth Wall according to FHWA MSE wall design guidelines [1]. Estimation of earth pressure based on Rankine's and Coulomb's theory was not applicable to narrow RE wall as one of the assumptions in conventional RE wall was that backfill was sufficiently long enough to create full rupture surface pass through entirely through reinforced soil zone. However, in case of narrow RE wall, due to boundary constraint and limited backfill width, the behavior of narrow RE wall differs in terms of the magnitude of earth pressure and internal stability such as resistance against pullout failure, especially at upper layers.

Janssen’s Arching theory which was developed for the analysis of silo pressure has been used by many researchers for calculation of earth pressure distribution behind narrow RE wall which was nothing but a reduction in earth pressure at greater depth due to side friction from two vertical boundaries and consequently stress redistribution within granular backfill. The magnitude of earth pressure for at-rest condition was found to be less than theoretical earth pressure values and in good agreement with Janssen's Arching Theory. Also, as aspect ratio decreases and as depth increases, lateral earth pressure behind narrow RE wall decreases. For active earth pressure conditions, Janssen's arching theory is applicable for the decreased value of ϕ as a progressive failure of soil mass occurred near the facing panel which decreases the value of internal friction angle of soil. Reduction in earth pressure was also a function of friction characteristics of boundary walls. As roughness of side walls increases, side friction (δ) increases which leads to an increase in the rate of reduction of lateral earth pressure. Also, it was concluded that when aspect ratio of the wall was between 0.25 and 0.6, the RE wall failed internally having mixed failure mode in which failure surface was bilinear and had an inclination less than Rankine active failure plane.

Numerical analysis on the development of tensile forces in reinforcements revealed that due to excessive surcharge loading, tension crack develops at the interface between narrow RE wall and existing stable wall which leads to separation of two walls and failure of narrow RE wall. Such type of cracks was not visually observed, which is the limitation of physical model testing for which finite element based software is proven to be an efficient tool to dictate the location of tension crack. The reason behind this is the inadequate development of tensile forces behind the narrow RE wall due to limited reinforcement length. The possible solution includes a connection between two walls (i.e., mechanical connection or friction connection), an extension of top layers into an existing wall or wrapped around facing of reinforcements at the rear end. Based on a field scale, numerical modeling and overall constructability, friction-based connection in which primary and secondary reinforcements overlapped to each other were proven to be a practical and innovative approach to increase the internal stability of combined wall systems.

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