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Review on Factors Considered and Rarely Considered in Design of Earth Retaining Structures

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Abstract: The road map to 2022 targets 44 express highways across widely variable soil sub-grades in our country. Out of Rs 20 cr/km approximately 2 cr is expected to be spent for flyover/underpass. They require Earth Structures of aprox 2 cr/km. The present handbooks, text books have well established design practices of Rankine and Coulomb's method of analyzing earth pressures. The development of theory before 1900 and recent R and D publications on factors influencing active earth pressures are summarized to minimize the probability of failures after construction and during life of structures. Short review of work before 1900 and brief impact of recent studies indicate earth structures will have to consider following additional factors into design. They are compaction of backfill by heavy vibratory rollers and type of loading on structures. The factors which are rarely considered are boundary conditions of back of wall, wall subjected to seismic activity and arching effect. This paper justifies their consideration in earth structures and recent Reinforced Earth retaining structures for constructing economical, durable and safe structures. The field instrumented observations for our structures is recommended to derive code of practice for coming years.

Key words: Earth retaining structures · Earth pressures · Compaction process · Design criteria's · Arching, Boundary conditions.

INTRODUCTION

The study, analysis and design of the Earth Retaining structures / Walls, requires fundamental concept and knowledge of earth pressure acting on the back of the wall or wall subjected to earth pressure and factor influencing the same. There are many factors reported by researchers which influence the active pressure in earth retaining structures such as Soil Displacement, Soil Strength and Strength Parameter, Water Table, Sloping Soil Surface, Wall Friction, Wall Inclination, Surcharge load, Seismic State, C-Φ Backfill Normally used in Construction, Influence of Compaction of Backfill, Effect of Rain, Seepage, Rotating, Freezing, Swelling etc, type of loading, Influence of Boundary Condition behind Wall, Practice in Hilly Region, Reinforcing Elements in the Backfill (grid and filter), Impact on State of Stress.

Historical Review of Old Structures (Pre 1900): Tremendous work had been done in difficult ground conditions before 1900 and from as early as 1700 theoretical models had been developed to address earth pressure and retaining wall design. The works of Gautier [1], Coulomb [2] and Rankine [3] are well known. Heyman [4], Skempton[5], Corradi [6] reviewed the subject. Corradi [6] cited Vauban as first engineer proving thumb rule for design of fort walls. They persisted through 19th century. Milligan, G.W.E *et al.* [7] applied theory to deep excavation, observation technique to measure active/passive pressures in field and deep diaphragm walls. (Moseley (1843) introduced Coulomb, Woltmann's (1799) reported new expression hydraulic engineering treatise. Poncelet (1840), Cuhlmann (1866), Winkler (1867) and Mohr's developed graphical method. Bell (1915) design monoliths at Dockyard in clay using shear parameters. Ritter, (1936) in Germany and Han Sen (1953) used theory after Second World War.)

Factors Influencing the Active Earth Pressures on Earth Retaining Structures:

Influence of Compaction of Backfill: Process of compacting backfill has undergone revolution with vibratory rollers in last two decades. For nondeflecting wall, cyclical loading, induced pressures, structural stresses have been reported to be of serious concern, Seed, *et al.* [8]. Duncan, *et al.* [9] reported increased mass horizontal pressure within compacted mass for plate

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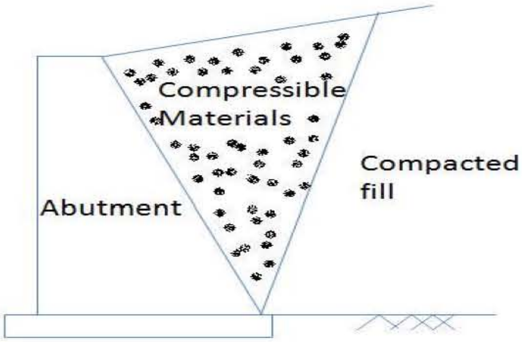

Fig. 1: Principle of controlled yielding

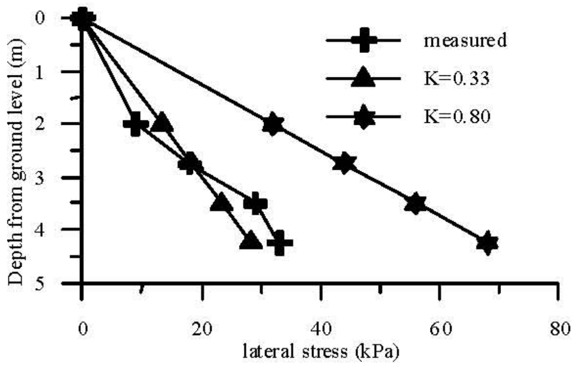

Fig. 2: Comparison of lateral stress actually measured (+), estimated theoretically (Ä) for design and adopted, by conventional theory

vibratory compactors. Prediction by EPCOMP2 program was accurate. For cohesive backfill, induced pressure decreased to at rest value over time. It was not so for sand backfill, unless wall moves. Near surface pressure attained passive state value. If ignored, in designs by practice critical problems could crop up during construction stage. Chen, *et al.* [10]'s model studies of rigid walls with compacted Ottawa sand shows: (a). vertical stress is unaffected. (b). horizontal pressure induced by compaction recorded Rankine state value. Confirming above phenomenon, Rajagopal [11] reported relief in high pressures by allowing small lateral movement. This movement is a function of shear resistance, mode of deformation and height of wall. Bridge abutments do not permit lateral expansion of backfill. The selected backfill, best compaction resorted to now a day to control settlement of approach to bridge imposes higher pressures. Similarly Broms, [12] confirmed higher stress at end of construction well compacted good fill. The case is not different in case of basement walls which have structurally zero lateral displacement. The K_a = 0.8 is recommended on basis of codes for culverts. Partos and Kazaniwsky [13] have evolved controlled yielding construction practice (selected material). A compressible layer (Figure 1) is designed and could also serve drainage/insulation requirements. In Gujarat [19] result of predicted, measured K value against design K = 0.8 shows good result (Figure 2).

Type of Loading: Ernesto Motta [14] state Generalized coulomb active-earth pressure for distanced surcharge. A closed-form solution has been given for the evaluation of the active earth pressure coefficient, which takes into account the effects of both the soil weight and the surcharge applied at a certain distance from the head of the wall. This allows one to take into consideration real-site conditions and to avoid uneconomical design. Seismic effects have also been taken into account in a pseudo-static way by means of horizontal and vertical-seismic coefficients. The use of the closed-form solution presented is not arbitrary but it is strictly dependent on boundary conditions. Fang, *et al.* [15] presents experimental data of earth pressure acting against a vertical rigid wall, which moved away from or towards a mass of dry sand with an inclined surface. It has been found that the earth pressure distributions are essentially linear at each stage of wall movement. Both the wall movement required for the backfill to reach an active state and the wall movement needed for the backfill to reach a passive state increase with an increasing backfill inclination. Experimental coefficients K_a and K_p tallies with coulomb's parameters, Hence for wall, on sloping backfill Rankine's theory is not appropriate. It may not be appropriate to adopt the Rankine theory to determine either active or passive earth pressure against a rigid wall sloping backfill. Terzaghi presented a graphical solution to the lateral earth pressure problem of cohesive backfill with an inclined surface. Mazindrani, *et al.* [16] presents an analytical solution to this problem. The values of active and passive earth pressure coefficient K_a and K_p for various values of Φ, β and $(C/\gamma z)$ are presented in tabular form and simple formula (Eq. 1).

$$K_pK_a = \frac{1}{\cos^2 f}\left[2\cos^2 \beta + 2\left(\frac{C}{?Z}\right)\cos f \sin f \pm \sqrt{\begin{bmatrix} 4\cos^2\beta\left(\cos^2\beta - \cos^2\phi\right) + \\ 4\left(\frac{C}{\gamma Z}\right)^2 \cos^2\phi + \\ 8\left(\frac{C}{\gamma Z}\right)\cos^2\beta \sin\phi\cos\phi \end{bmatrix}}\right] - 1 \quad (1)$$

Where: K_p = Passive earth pressure coefficient, K_a = Active earth pressure coefficient, Φ = Angle of internal friction in □, γ = Unit weight in kN/m^3, β = Retaining wall of height H with inclined cohesive backfill angle in□, C = Cohesion of the backfill in kPa, Z = Depth to any point on the vertical back of the retaining wall from the level ground surface in m.

Gnanapragasam, [17] developed analytical solution to determine active lateral pressure distribution on retaining structures with C-Φ soil backfill with inclined ground surface. Slope of failure is function of overburden pressure and becomes shallower with depth forming a curvilinear failure surface. It can be adopted for study of sustainability of slope and can be programmed in computer. Greco [18] reported analytical solution for evaluating active pressure with line load based on coulomb's approach and its point of action.

Factors Influencing the Active Earth Pressures on Earth Retaining Structures Which Is Rarely Considered in Design:

Boundary Conditions of Back of Wall: Sam and Israel. [19], based on centrifuge modeling for nearby rock boundary of backfill, suggest progressive failure in soil result in reduced Φ (K=1-sinΦ). The effect of base projection on the active earth pressure is presented by Barghouthi, [20]. The failure wedge is bounded by two surfaces, one of them intersecting into the soil and the ground surface and the other one intersecting the wall. The inclination of the first surface is independent of the wall friction and the length of base projection. The inclination of the resultant earth pressure force will always be greater than the slope of the backfill and less than the angle of wall friction. If the wall is frictionless, the inclination will be less than the slope of backfill. The magnitude of earth pressure force will always be greater than that given by Coulomb solution for a wall without base projection and less than the force given by a Rankine analysis on the vertical plane through the heel with no wall friction. All these conclusions are made in the case of wall interference with the shear zone. If there is no interference then the Rankine solution is applicable. Kim and Barker. [21] gives conventional design of retaining walls and bridge abutments; the lateral earth pressure due to live load surcharge is estimated by replacing the actual highway loads with a 600 mm layer of backfill. A number of researchers have shown that the pressure exerted on the wall due to live load surcharge is greater near the surface and is diminished nonlinearly throughout the height of the wall. The heavier highway loads and the demonstrated nonlinear earth pressure distribution require a need for a more rational method for obtaining the equivalent height of backfill. This paper discusses theoretical background, an analytical approach to estimation of actual earth pressure, a number of innovative approaches to obtain a simplified pressure distribution, an extensive parametric study, calibration procedures for the traditional method. Smethurst and Powrie. [22] gives a multiple Coulomb wedge analysis using effective stress soil parameters is used to estimate the pressure distribution on the wall as the result of the presence of the berm. Its use in limit equilibrium wall stability calculation is compared with two commonly used empirical methods of representing a berm in such an analysis. It is shown that the raised effective formation method of representing a berm-which gives good results in an un-drained or total stress analysis-is un-conservative for an analysis using effective stress soil parameters. A modified raised effective formation method is proposed.

Wall Subjected to Seismic Activity: Nadim and Whitman. [23] proposed seismically induced movement of gravity retaining walls. The methods generally ignore the effects of ground motion amplification in the backfill on the seismic behavior of the wall. Results obtained with a finite element model capable of taking into account the amplification of ground motion in the backfill, while computing permanent distortions, are presented. Implications of these results for design are also considered. Isao *et al.* [24] performed One-directional (horizontal) shaking-table experiments on one sandy and two cohesive saturated backfills to investigate the dynamic water and total lateral pressures against rigid nonyielding walls during earthquakes. It was found that the dynamic water pressure against the wall is generated due to two different sources. The first source is Westergaard-type, which is due to the flow of free water in nondeformable backfill soil skeleton and the second is due to the deformability of backfill soil skeleton under undrained conditions. For highly permeable backfill soils, the first source dominates in the generation of pore pressure and the second source dominates for cohesive backfills. The dynamic water pressure resultants of this type for cohesive backfills are nearly as much as the value of Westergaard's but is applied at approximately 0.6H from the bottom of the backfill. The dynamic total pressure resultants for cohesive backfills are nearly twice Westergaard's dynamic water pressure resultant and also applied 0.6H from the bottom of the backfill. Li. [25] studied dynamic behavior of a rigid wall by the elastic approach. The analyses presented by Veletsos and

Younan are extended to include foundation flexibility and damping. A closed-form analytical Solution is obtained by assuming a simple backfill-foundation interface condition. It is shown that both ‘‘static’’ and dynamic base shears may be reduced by the foundation effects such that the base shears computed by the elastic approach may be of the same order as that estimated by the Okabe-Mononobe equation, even for a rigid gravity wall. A rotating block method is developed to calculate the rotational displacements of gravity retaining walls based on rigid foundations under seismic loading by Zeng and Steedman. [26]. The influence of ground motion characteristics on computed wall deformation was evaluated. The procedure was validated by data from centrifuge tests and this method is also applicable for the most complex cases when the sliding and rotation of a gravity wall are coupled. Rathje and Bray. [27] presented a coupled analytical model that captures simultaneously the fully nonlinear response of the sliding mass (necessary for intense motions) and the nonlinear stick-slip sliding response along the slide plane. The proposed sliding model is validated against shaking table experiments of deformable soil columns sliding down an inclined plane. The effect of sliding on the response of earth structures is evaluated and comparisons are made between sliding displacements calculated using coupled and decoupled analytical procedures with linear and nonlinear material properties. Results indicate that a decoupled analysis is adequate for earth structures that are not expected to experience intense, near-fault motions. Huang and Chen. [28] developed a new pseudo-static method to evaluate the seismic stability of retaining walls situated on slope, with Sliding failure along the wall base and bearing capacity failure in the foundation slope. Results of the analysis showed that seismic stability of the wall against bearing capacity failure may be greatly overestimated when the inertia of soil mass is not taken into account. This highlights the importance of improving the strength of backfilled soils in the passive zone when constructing soil retaining walls on slope and suggests a modification of the current design considerations for soil retaining walls situated on slope. Shukla, *et al.* [29] reported parametric study for total active force on a wall with C-Φ soil backfill considering both the horizontal and vertical seismic coefficients. He has developed design charts for various combinations of horizontal and vertical seismic coefficients (K_h and K_v) and values of cohesion and angle of shearing resistance for estimating the total active force on retaining wall for C-Φ soil backfill for practical application.

Arching Effect: Rain, Seepage, Rotating, Freezing, Swelling: Sherif, *et al.* [30] reports experimental work on Ottawa sand on the magnitudes and distribution of static at-rest stresses behind a rigid wall as a function of soil densification and on static active stresses mobilized behind a rigid wall rotating about its base. Based on these experiments on Ottawa sand, the following conclusions are drawn: (1) The stress distribution behind a non-yielding rigid wall is hydrostatic; (2) the well known Jaky equation applies only when the backfill is deposited at its loosest state; and (3) when the backfill behind the wall is either compacted or vibrated to increase its density, the magnitude of the at-rest stresses increases due to densification and the total at-rest stress exerted on the wall will then be the sum of the stresses due to gravity effects and the locked-in horizontal stresses due to densification. For a rigid wall rotating about the base: (1) The static active stress distribution behind the wall is also hydrostatic; (2) soil densification decreases the magnitudes of active stresses behind such walls; (3) the magnitude of the active stresses behind a wall rotating at its base can be obtained by the classical Coulomb equation; and (4) the state of active stress propagates downward from the surface of the soil with increasing wall rotation. Sorochan and Kiln. [31] proposed a procedure for determining the effect of the displacement of a retaining wall on the stress-strain state of the mass swelling soil adjacent to it and the lateral pressure acting on it using the finite-element method. The results of calculations performed in accordance with the method and data derived from a field experiment are compared. Paik and Salgado. [32] stated effect of arching in backfill and new formula is proposed for calculating the active earth pressure on rigid retaining wall undergoing horizontal translation. Ying, *et al.* [33] theoretically analyzed the shape of minor principal stress arch considering the effect of soil internal friction angle on the inclination of slip plane behind a retaining wall and the partial development of wall friction. Their study shows that the Shape of minor principal stress arch behind the retaining wall are different from those proposed by others. Average vertical earth pressures were computed according to the shape of minor principal stress arch. The coefficient of earth pressure versus the angle of internal frictional and the angle of wall friction was obtained. Using the coefficient in the method of horizontal differential element to compute active earth pressure on retaining wall, the theoretical formulae of the unit earth pressure, the resultant forced and the point of application of the resultant force were derived. The proposed method is compared with the method by others and some experimental data. Benmebarek, *et al.* [34] deals with the effect of seepage flow on the lateral earth pressures acting on deep sheeted excavations in cohesionless soil. The computation of the passive and active earth pressures in the presence of hydraulic gradients is performed using the explicit finite difference method implemented in Fast Lagrangian Analysis of Continua (FLAC) code. The available effective passive earth pressure coefficients in the presence of upward seepage forces are given for both associative and non-associative material. The presented solutions show that the soil dilation angle influences the effective passive earth pressures for large internal friction angle values of the soil. They also show that the effective passive pressures diminish with the hydraulic head loss. Good agreement is observed between the present results and those using an upper-bound approach in limit analysis for an associative material. For the active case, the effect of downward seepage forces on the active earth pressures is investigated. The numerical results show a significant increase in the effective active earth pressures due to a hydraulic head loss. It is also shown that the dilation angle influences the effective active earth pressures for large internal friction angle values. Alekseev. [35] cited a procedure for and results of field and laboratory studies of the forces and deformations that develop during the freezing-thawing of heaving soils behind retaining walls. It has been established by field investigations conducted from 2001 through 2004 on a section of retaining wall in an open transportation tunnel in Sergiev-Posad that the horizontal pressure induced by frost heaving of the soil (clayey loam) increases after the air temperature has been lowered over a period of from 1 to 5 days; this is associated with gradual freezing of the soil and migration of water from the underlying layers of unfrozen soil. The horizontal frost-induced pressure varies in a jumpwise manner and attains a maximum at the contact between the soil and retaining wall and its value increases with decreasing temperature and increasing thickness of the freezing layer of soil. Maximum horizontal frost-induced pressure of the soil behind the retaining wall was 0.19-0.50 MPa. The pressure due to frost heaving decreases with increasing distance from the wall. The horizontal pressure of the soil varies over the depth as a function of the temperature and physical properties of the soil. Quantitative values are obtained and dependencies of the pressure and deformations resulting from frost heaving and thaw-induced settlement on moisture content, density and freezing conditions are established from laboratory investigations on clayey-loam specimens extracted in an experimental section of the retaining wall. A procedure is developed for determination of the pressure induced by the frost heaving of soil with allowance for conversion factors obtained in accordance with similarity theory, which take into account the compressibility of the unfrozen layers of soil and the actual frost depth. Results of investigations of the frost-induced pressure exerted by soils under laboratory and field conditions indicated good agreement and differ by no more than 10%. Thomas, *et al.* [36] offers a method for estimating the magnitude of lateral swell pressure that may be exerted on such structures when expansive cohesive materials are used as backfills. Traditional design methods do not consider the lateral swelling pressures that expansive soils exert upon wetting. In addition, stability analysis results depicting the impact of swell pressures of these materials on calculated Factors of Safety (FS) values for external stability are presented.

Discussion from Literatures: The study brings out the need to modify the present practices in design of Earth Retaining Structures in use over three decades taking into account the following: 1. Compacting Non Cohesive / Cohesive soil backfill by vibratory rollers, plate compactors etc simultaneously with raising of wall. 2. Use of cushion (Figure 1). 3. Type of loading and distance of loading. 4. Seismic condition of wall is in appropriate seismic area. 5. Swelling potential of backfill in CH Expansive soil area. 6. Climatic condition of freezing and throwing. 7. Boundary condition of backfill. 8. Arching at back of wall due to differential movements in different filling material.

The design and construction failures of recent times could be analyzed with these suggestions. The field instrumented observations for our structures could be used to derive a code of practice is recommended.

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