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Transition of earth pressure on rigid retaining walls subjected to surcharge loading

ABSTRACT: Retaining walls are an integral part of various infrastructural projects and are used to support deep excavations, or steep embankments, and deep basements. The earth pressure on these walls plays a crucial role in deciding the cross-sectional dimensions of the wall. An attempt was made in this research study to examine the variation of both the magnitude and distribution of earth pressure at-rest, and with reference to various possible wall movements, necessary to mobilize the active and passive earth pressures on the wall. Experimental studies were carried out on small-scale retaining walls supporting a cohesionless backfill material, and subjected to surcharge loading. Wall movement was modeled in the laboratory by allowing the wall to rotate about its base to simulate the case of rigid cantilever retaining walls. It was found that under surcharge loading, the earth pressure on the wall was gradually decreased as the wall moved away from the backfill but increased as the wall moved towards the backfill. It was also observed that the earth pressure due to surcharge load was greater near the top of the wall and decreased nonlinearly with depth down the wall. The lowest earth pressure occurred at the bottom of the wall, in contrast to the usual assumption that the earth pressure due to surcharge loading is uniform throughout the retaining wall. Finally, it was demonstrated that the distance between the surcharge load and the edge of the wall had a significant effect on the measured earth pressure values.

KEYWORDS: Rigid retaining wall, magnitude, distribution, earth pressure, laboratory studies, surcharge loading.

1. INTRODUCTION

Retaining walls withstand pressures from retained materials and surcharge pressures due to movement of vehicular traffic or loads from foundations of the adjacent buildings on their backfills. For the design of earth retaining structures, it is essential to have proper knowledge on the magnitude and distribution of earth pressure on the retaining wall due to the factors cited above. At-rest condition is generally defined as a stage of no wall movement. Initial active/passive (plastic) condition refers to a stage of rotation or translation of a retaining wall when any soil element behind the retaining wall first develops a sufficient limiting deformation to achieve initial plastic state. Whereas, fully plastic conditions occurs when all the soil elements within the failure zone along the entire depth of the wall is in plastic state.

In routine design practice, the earth pressures due to backfill are usually assumed to follow a hydrostatic pressure distribution. However the above assumption is valid only for a particular limiting case when the wall is vertical and perfectly smooth, and the backfill soil is in a state of plane stress. In the case of surcharge loading, the thrust on the retaining wall is calculated by hybrid approach, where the thrust due to surcharge is calculated analytically by means of elastic theory and added to that in the absence of surcharge, calculated using Coulomb's method or any other thrust theory. However, previous experimental observations revealed that the additional earth pressure on the retaining wall, due to the surcharge, was non-uniform over the wall height and diminishes from a maximum value near the surface of the backfill to a minimum near its base (Vargin 1968).

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DOI 10.3328/IJGE.2012.06.04.427-435

Evaluation of magnitude and distribution of earth pressures on the retaining walls, subjected to different loading and boundary conditions, modes of wall movement, and material properties is a topic of immense interest for researchers worldwide for quite a long time. However, most of the available studies are either analytical or numerical in nature, and there is no common consensus on the experimental findings reported by previous researchers. Hence, experimental evaluation of earth pressure on retaining walls is still a challenging task, and the work reported in this paper focuses in this direction.

2. LITERATURE REVIEW

Earth pressure under surcharge loading

The active thrust on retaining walls is often calculated using Coulomb's method employing analytical solution of Mueller Breslau (1906). Gerber (1929) and Spangler (1936) conducted experiments to measure the pressures behind a wall due to point loads, line loads and area loads. The horizontal pressure distribution obtained from the tests generally agreed with the Boussinesq's half-space (1885) solution, which is analytical in nature and based on elastic theory, but the magnitudes were about twice those calculated by Boussinesq's equation.

Vargin (1968) observed through large scale model tests that pressure due to the surcharge has a damped character, with a maximum at the surface and a minimum at the base of the wall. Also the increase in pressure was proportional to increase in surcharge. Based on Vargin (1968) experiments, Shvetsov (1974) highlighted that the effect of surcharge was constant for all possible slip planes and the maximum pressure on a retaining wall with and without a surcharge will correspond to the same surface of sliding.

Steenfelt and Hansen (1983) suggested that the elastic solution was only reasonable for unyielding structures whereas Coulomb's approach is more appropriate for analyzing soils in the active state of failure. Jarquio (1981) and Wang (2007) concluded that for vertical uniform load, the lateral force and centroid location were quite different for both isotropic and anisotropic backfills. Georgiadis and Anagnostopoulos (1998) concluded that the experimental lateral pressures on sheet pile walls to be sufficiently close to those predicted by Coulomb's method and much lower than those obtained using the elastic approach. Guidelines have been provided in Geoguide I (2000) on the magnitude of pressure and its distribution, depending on the distance between the retaining wall and the point of application of the load. Kim and Barker (2002) observed that the pressure due to surcharge load was greater near the surface but diminished nonlinearly throughout the height of the wall.

Table 1. Physical properties of the Indian Standard Sand (Grade-II)

Parameter	Value
Effective particle size, D_{10} (mm)	0.44
D_{30} (mm)	0.50
D_{60} (mm)	0.63
USCS classification	SP
Specific gravity of soil solids, G_s	2.65
Maximum void ratio, e_{max}	0.77
Minimum void ratio, e_{min}	0.54
Maximum unit weight, γ_{max} (kN/m^3)	16.96
Minimum unit weight, γ_{min} (kN/m^3)	14.70
Friction angle (Direct Shear Test), ϕ	30°

Earth pressure under various wall movements

Terzaghi (1934) showed that the earth pressure estimated based on classical theories of Coulomb and Rankine can provide satisfactory results only when lateral soil deformation is large enough to fully mobilize the shear strength of the soil. Terzaghi (1936) pointed out that for a wall rotating about its base, the active earth pressure is more or less hydrostatic; whereas for other types of movements such as translation, rotation about the top or centre of a wall, the distribution is nonlinear.

Roscoe (1970) demonstrated that the magnitude, direction and point of application of resultant earth force are dependent on the mode of movement of the wall. Experiments by Ishihara and Matsuzawa (1973) revealed that the point of application of the resultant and the mobilized angle of wall friction is a function of mean wall displacement.

In many practical cases, the movement of the retaining wall is restricted or less than the magnitude necessary for the development of the active condition, which leads to development of higher lateral earth pressures than the active lateral earth pressures. Sherif et al. (1982) concluded from experiments on model retaining wall that at-rest pressures behind non-yielding rigid retaining wall and active earth pressures behind wall rotating about the base were hydrostatic in nature. Sherif et al. (1984) pointed out that the horizontal deformation necessary to mobilize the active state of stress at each transducer level is almost the same for the rotation about the base mode indicating that the lower portion of the backfill soil requires much more wall rotation about its base in order to reach an active state of stress. Also, the horizontal displacement necessary to mobilize the active state of stress is independent of soil angle of internal friction or density.

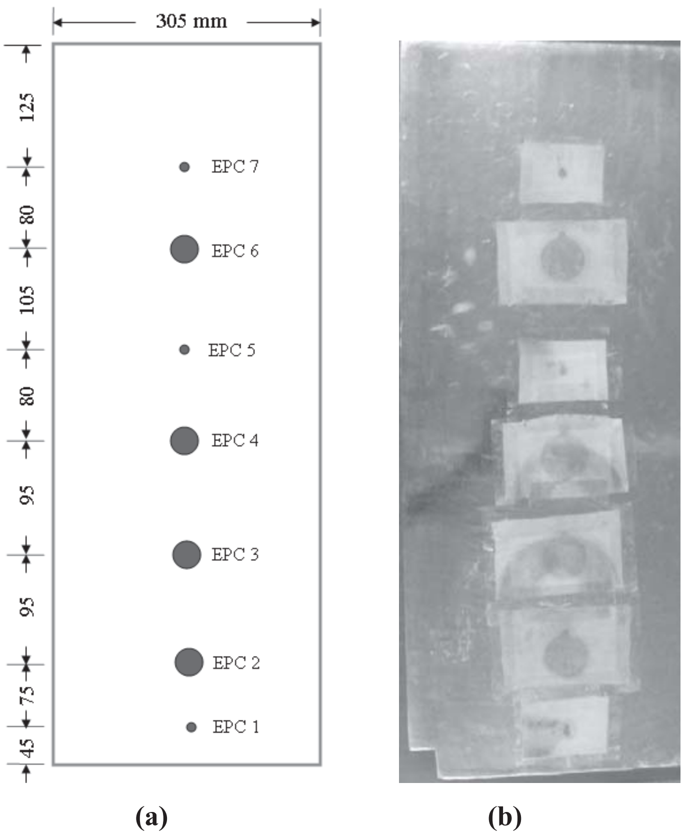

Figure 1. Location and identification of pressure cells fixed on steel plate (a) Schematic diagram (b) Pictorial view.

Through experiments on rigid retaining wall, Fang and Ishibashi (1986) concluded that the wall deformation necessary to mobilize the active state of stress for a rigid retaining wall was independent of the type of wall movement, viz. rotation about top, rotation about bottom, and translation. Fang et al. (1996) concluded that the magnitude of passive thrust and its point of application were significantly affected by the mode of wall displacement. Fang and Lee (2006) found that after a wall movement of about 14% of wall height, the passive thrust attained a constant value irrespective of the backfill density. Zhang et al. (1998) proposed new earth pressure equations based on Coulomb and Rankine's theories which can be used to determine lateral earth pressures due to normally consolidated cohesionless soil for any lateral deformation between active and passive states of stress, including the at-rest state. These solutions, involving different constitutive relations for the soil and the soil-structure interface, allow further insight into the relationship between wall movement and lateral earth pressure.

Displacements required for fully plastic equilibrium condition

According to Terzaghi (1934) wall displacement (Da) required for the entire soil mass behind the wall to reach the fully active state varies from 0.0014 H for dense sand and 0.0084 H for loose sand (where H=height of wall). Clough and Duncan (1971) observed these displacements as 0.0023 H for wall rotating about the base and 0.0026 for a translating wall in medium dense sand. Results of Nakai (1985) indicated incomplete mobilization of shear strength for rotating about the top in dense sand even at maximum wall displacement of 0.013 H. Experiments by Sherif et al. (1984) and Fang and Ishibashi (1986) shown that the displacement needed for shearing resistance of the soil behind the wall to mobilize fully was 0.0003 H. Comparing results from model tests on retaining walls for various modes of movement, Fang et al. (1993) concluded that the displacement value needed for full mobilization of shear strength would be within the range of 0.003H to 0.005H, irrespective of the mode of movement and density of backfill.

Need for the present study

Limited studies were conducted to experimentally obtain the magnitude, variation and distribution of earth pressure on retaining walls, subjected to surcharge loads, when wall moves either away from backfill (active movement) or towards backfill (passive movement) from its original at-rest position. The above studies emphasize that the notion of hydrostatic earth pressures due to backfill and uniform earth pressure due to surcharge loads are far from reality, and may grossly overestimate the earth pressures, in many

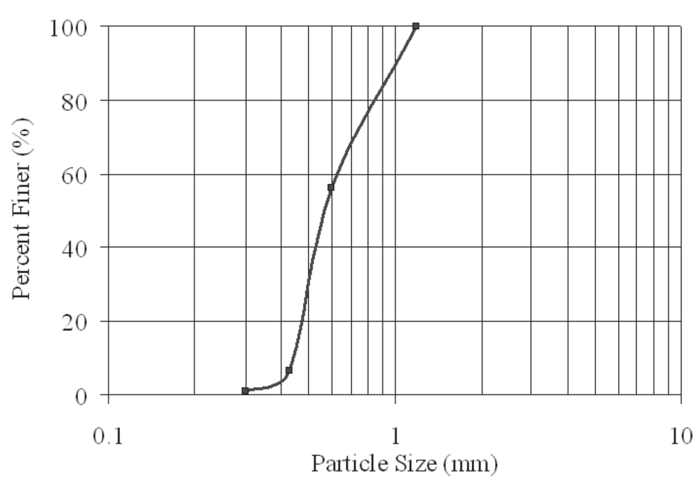

Figure 2 Gradation Curve of the material used in the present study.

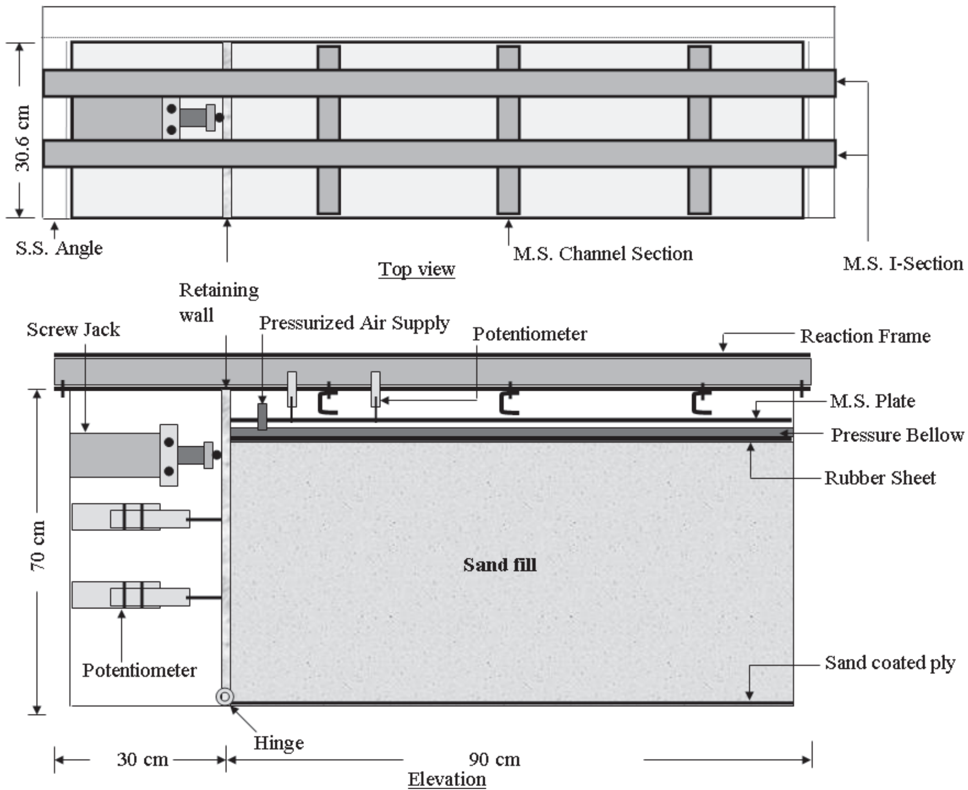

Figure 3. Details of experimental set up.

cases. In view of the invent of new design procedures, such as reliability and performance based methods, aimed at achieving more economical and reliable designs, the level of conservatism involved with the conventional procedures for estimating the earth pressures on retaining walls, needs to be evaluated. These rational approaches are slowly replacing the conventional deterministic methods, in geotechnical engineering, and are the basis for developing more consistent and reliable design methods in codes for day-to-day use.

Hence, the objectives of the present study focus on obtaining the magnitude and distribution of earth pressure on the retaining wall, with different wall movements, under the effect of surcharge loading, through small-scale model experiments. The following cases are considered in the study:

1. Retaining wall at at-rest condition with incremental surcharge pressure;
   a. when the edge of the surcharge load is adjacent to the wall
   b. when the edge of the surcharge loading is at a distance of h/4 from the wall, where h is the height of backfill
2. Retaining wall moves away from backfill, under maintained surcharge loading; and
3. Retaining wall moves towards the backfill, under maintained surcharge loading.

3. APPARATUS AND EXPERIMENTAL PROGRAM

The model retaining wall was built of stainless steel plate of 0.70 m height, 0.305 m width and 16 mm thickness. A total of seven diaphragm type earth pressure cells (EPC) were arranged flush with the retaining wall surface and into the recess. The wall was placed in a stainless steel test tank of 1.2 m length, 0.31 m width and 0.7 m depth. Three sides of the test tank consisted of 16 mm steel plates perfectly welded while a longer side consisted of 25 mm thick Perspex sheet. The floor of the tank was made of 25 mm thick steel plate welded to all sides of the tank and consisted of recesses with internal tapping at each 5 cm spacing so as to connect the model retaining wall at the desired place and to change the location of the wall if required. The bottom of the tank consisted of 5 mm plywood, placed above the bottom steel plate, on which epoxy resin was spread and sprinkled with the same sand as that used as backfill. In order to achieve plane strain conditions all the sides of the tank were pasted with 10

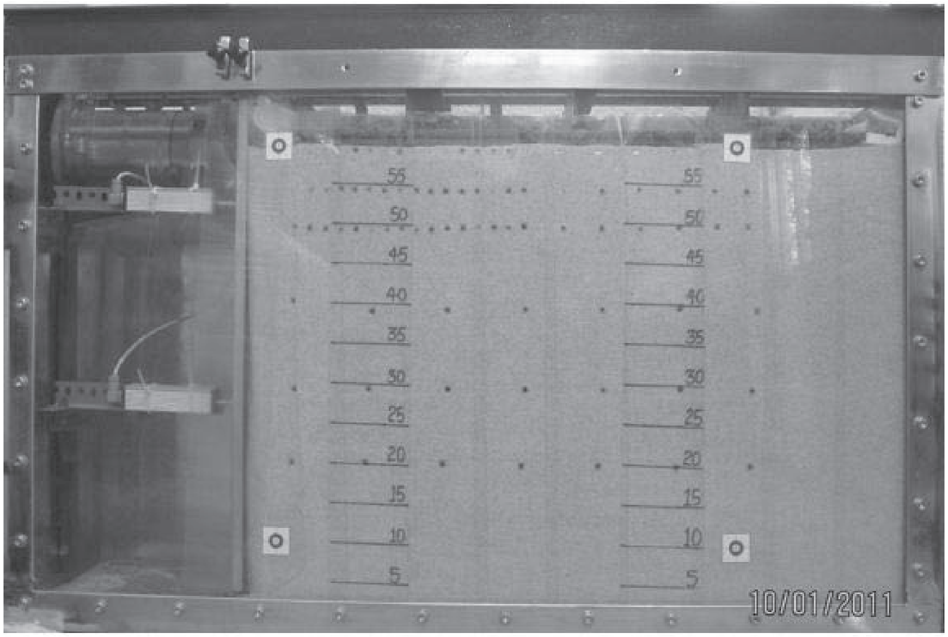

Figure 4. Pictorial presentation of experimental set up.

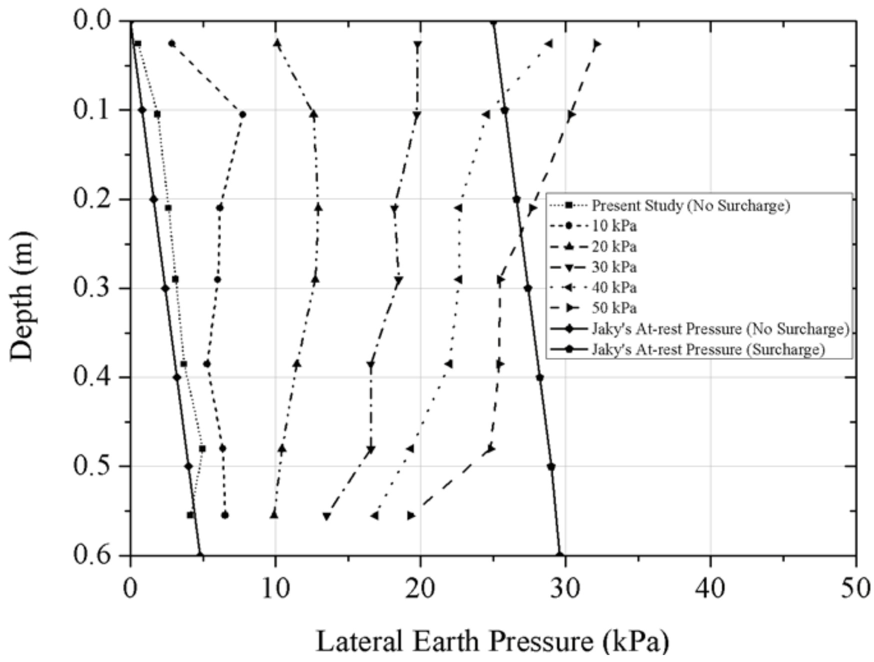

Figure 5. Distribution of at-rest earth pressure, when edge of the surcharge load is at the face of wall.

cm wide greased polyethylene sheets of 60 μm thick with an overlap of 1 cm, in accordance with the recommendations of Tawfiq and Caliendo (1993). In order to obtain reliable measurements of earth pressures, each EPC was calibrated with the same backfill material and loading system to which they were subjected to during the earth pressure measurement (Dave & Dasaka, 2011), and calibration factors were obtained for each earth pressure cell.

The sand bed was prepared using a traveling pluviator of the type developed by Dave and Dasaka (2010), which

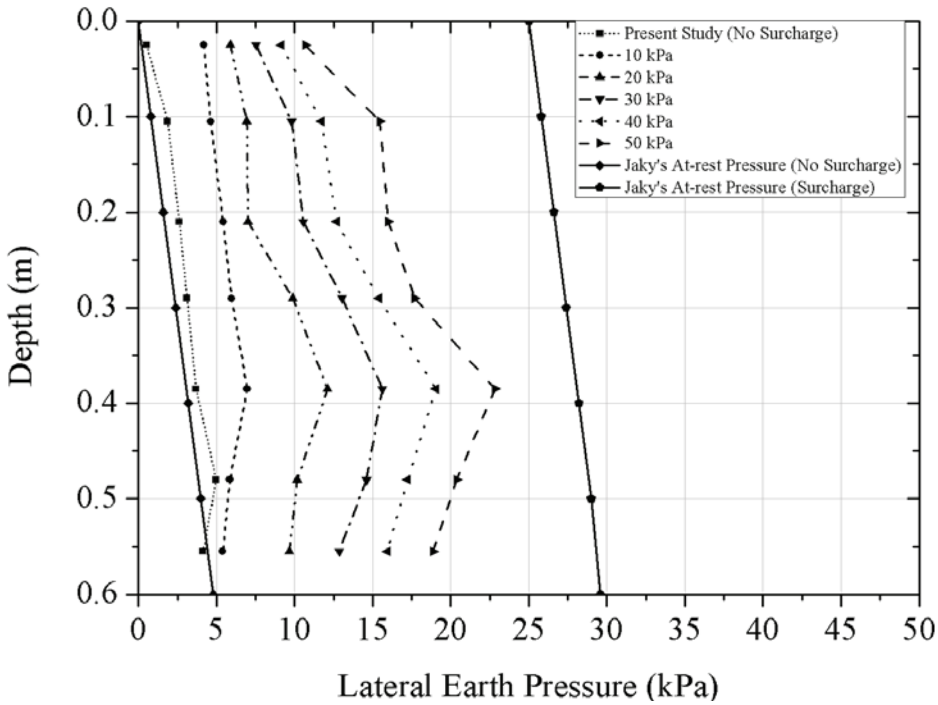

Figure 6. At-rest earth pressure, when edge of surcharge load is at h/4 distance from face of wall.

consists of an orifice and diffuser system. Sand flow from hopper was regulated using orifices of different sizes, and uniform flow of sand obtained through a set of 10 diffuser sieves. The sand bed density was varied by changing either the orifice size (controls sand flow) or height of fall of sand particles. A mechanical jack of 20 ton capacity was connected firmly to a steel strip which was fixed to the non-backfilled side of test tank. The jack assembly was used to hold the retaining wall in an up-right position to obtain the at-rest condition and to apply lateral movement to the wall in active and passive directions to achieve plastic conditions. Four linear potentiometers, two in horizontal and two in vertical directions, were installed to measure displacements during the test and to ensure no horizontal movement in the at-rest state. NI-cDAQ- 9172 data acquisition system was used as a source of excitation to earth pressure cell (EPC) and to acquire continuous data during experiments and NI LabVIEW SignalExpress for data logging.

Indian Standard sand (commercially known as Ennore sand) of Grade-II, classified as SP as per unified soil classification system, was used in the experiments, and the corresponding particle size distribution curve is as shown in Fig. 2. Some of the physical properties of the sand are shown in Table 1. Throughout the present study, the backfill was compacted to achieve 68% relative density.

The model retaining wall was placed 0.3 m away from the non-backfilled end and hinged to the tank bottom by using specially designed clamps, leaving a space of 0.9 m × 0.31 m × 0.6 m as backfilling side of the tank (or front side of the wall). The 0.3 m wide space on the non-backfill side was used to place the jack assembly, to move the wall on either side from its at-rest position, and to fix linear potentiometers to measure horizontal wall displacement during the experiments (Fig. 3 and 4). Markers were placed in the backfill at 0.2, 0.3, 0.4, 0.5, 0.55, and 0.6 m height from the tank bottom, to observe relative wall movement, as shown in Fig. 4.

To apply uniformly distributed surcharge load on the backfill, a rubber bellow was placed over an 8mm thick rubber sheet lying on the backfill. A steel plate of 10 mm thickness was placed on the rubber bellow such that when inflated with compressed air, the plate moved upwards to mobilize reaction frame, which was rigidly connected to the tank, thereby transferring pressure to the sand fill.

4. TESTING PROCEDURE

After backfilling the sand up to 60 cm height in the testing tank, surcharge pressures, in the range of 0–50 kPa were applied on the backfill. The surcharge pressures were increased in steps of 10 kPa, ensuring steady readings before applying the next increment. Steady state reading took approximately 1-2 minutes to achieve. The earth pressures sensed by EPCs were constantly monitored throughout the

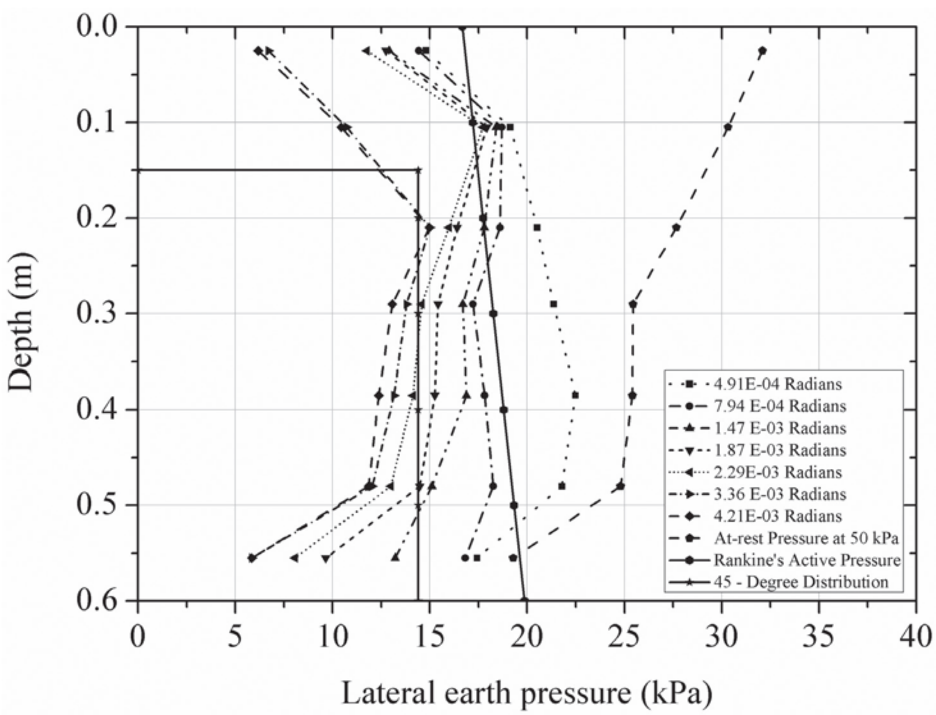

Figure 7. Distribution of earth pressure due to wall movement in active direction, under surcharge loading.

experiment. The magnitude and variation of at-rest earth pressures were measured along the height of the wall when a surcharge was placed adjacent to the face of the wall, and at h/4 (0.15 m) distance away from wall as shown in Figs. 5 and 6, respectively. Earth pressure is measured after application of each displacement. During the application of active movement surcharge pressure of 50 kPa was maintained throughout. The magnitude and distribution of earth pressure under maintained surcharge, when wall moves in active direction is shown in Fig. 7. The rotation of the wall about its base was expressed in terms of radians. To achieve passive movement, the wall was slowly pushed towards the backfill by manually operating the screw jack, while maintaining a surcharge of 50 kPa, then earth pressures measured after each displacement. Measured earth pressures on the wall under passive movement are shown in Fig. 8.

5. RESULTS AND DISCUSSION

Earth pressures are also estimated on the at-rest wall, using the well established equation developed by Jaky (1944), and reported in Fig. 5 and 6, for backfill with no surcharge and a surcharge load of 50 kPa. It can be observed from Fig. 5 and 6 that the measured earth pressure along the height of wall, without surcharge loading, is a little higher compared to that obtained from Jaky's equation. The earth pressure is observed to increase with depth in both cases. From Fig.5 it can be observed that the measured earth pressures increase with increase in surcharge loading, at all the locations. It is also evident from Fig. 5 that the effect of surcharge on the earth pressure decreases with depth, with maximum earth pressure observed near the top of wall and minimum near the bottom. Upton the mid height of wall, Jaky's equation underestimates the earth pressure, whereas it overestimates in the remaining half section. The magnitude of maximum earth pressure is found to be closer to that estimated by Jaky's equation. The magnitude and distribution of earth pressure when a surcharge is placed at h/4 distance away from the top of the wall is presented in Fig. 6. It is clearly observed that as distance between surcharge and wall increases, its effect on earth pressure reduces. Though earth pressure was found to increase with depth, its magnitude is quite lower than that estimated by Jaky's equation.

Active earth pressures are estimated by well established Rankine's theory and mostly used practical approach of 45°distribution, and compared with results obtained from the present study, as shown in Fig. 7. It is found that Rankine's method over-estimates the active earth pressure, however, the observed pressures are closely matching with that found using 45°distribution method in the upper half of the wall. Some reduction in observed pressure is found in

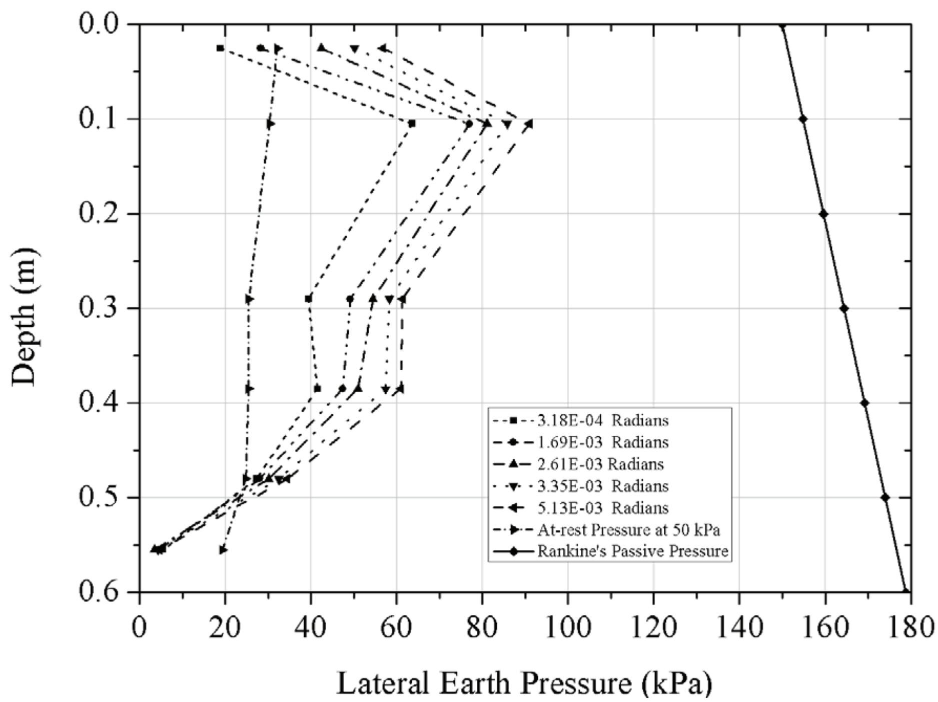

Figure 8. Distribution of earth pressure with movement of wall in passive direction, under surcharge loading.

lower half, with minimum near the base. Also the effect of surcharge on the earth pressure in upper half part is reduced as the wall moved away from backfill. During movement of wall towards backfill under the surcharge loading, the wall could not be moved sufficiently to form a passive wedge, due to constraint from top surcharge plate and practical limitations in jack movement, which did not allow the upward movement of soil mass. The increase in measured earth pressures during passive movement is found to be greater along the upper part of the wall and decreased continuously with further depth, for applied wall movements. The measured earth pressures are compared with Rankine's passive earth pressure, as shown in Fig. 8. The results presented in this paper are based on limited experimental findings, and more research in this direction is warranted, for further understanding of the behavior of retaining walls subjected to surcharge loads.

CONCLUSIONS

The present study aimed at experimentally evaluating the magnitude and variation of earth pressure on model retaining walls, subjected to surcharge loading. The following are some of the important conclusions drawn from the present study.

1. Experimental studies on earth pressure on retaining walls under surcharge loading suggested continuous decrease in earth pressure, when wall moved away from backfill and continuous increase in earth pressure as wall moved towards backfill.
2. The earth pressure due to the influence of surcharge load is greater near the surface and diminishes nonlinearly throughout the height of the wall, irrespective of the movement of the wall.
3. The magnitude of measured at-rest earth pressure matches with that obtained by Jaky's theory, when surcharge is close to the top of wall.
4. The effect of surcharge load on measured earth pressure is found to decrease with increase in distance between the wall and edge of the surcharge load.
5. The measured active earth pressure matches closely with that estimated by a 45° distribution method.
6. Experimental determination of passive earth pressure under surcharge is challenging due to very high pressure ranges and associated experimental difficulties involved.

ACKNOWLEDGEMENTS

The work reported in this paper is substantially supported by the Department of Science and Technology (DST), India, through Project No. SR/FTP/ETA-69/2008. The suggestions made by the reviewers are also appreciated, as they were very useful in modifying the manuscript.

REFERENCES

Boussinesq, J. (1885). *Application des potentiels à l'Étude de l'Équilibre et due mouvement des solides élastiques*, Gauthier-Villars, Paris.

Clough, G. W. and Duncan, J. M. (1973) Finite element analysis of retaining wall behavior, *J. of Geotech. Engg, ASCE*, 97(12), 1657-1673.

Dave, T. N. and Dasaka, S. M. (2012). "In-house calibration of pressure transducers and effect of material thickness," *Geomech. and Engg. - An Intl. J., Techno Press,* Accepted, In Press

Dave, T. N. and Dasaka, S. M. (2012). "Assessment of portable travelling pluviator to prepare reconstituted sand specimens," *Geomech. and Engg. - An Intl. J., Techno Press*, 4(2), 79-90.

Fang, Y. S. and Ishibashi, I. (1986). "Static earth pressures with various wall movements," *J. Geotech. Engg.*, 112(3), 317-333.

Fang, Y. S., Cheng, F. P., Chen, R. C. and Fan, C. C. (1993). "Earth pressures under general wall movements," *J. Geotech. Engg.,* 24(2), 113-131.

Fang, Y. S., Chen, T. J., and Wu, B. F. (1996). "Passive earth pressures with various wall movements," *J. Geotech. Engg., ASCE*, 120(8), 1307-1323.

Fang, Y. S. and Lee, C. C. (2006). "Passive earth pressures with various backfill densities," *Proc. of 6th ICPMG – Phy. Mod. in Geotech.*, Taylor & Francis Group, London, 1081-1086.

Georgiadis, M. and Anagnostopoulos, C. (1998). "Lateral pressure on sheet pile walls due to strip load," *J. Geotech. and Geoenv. Engg.*, 124(1), 95-98.

Geoguide I (2000). *Guide to retaining wall design*, Geotechnical Engineering Office, Civil Engineering Department, The Government of the Hong Kong, Special Administrative Region.

Gerber, E. (1929). "Discussions of investigations of the distribution of pressure on locally loaded sand," *A. G. Gebr.* Leemann, Zurich.

Ishihara, M. and Matsuzawa, H. (1973). "Application of plane strain tests on earth pressure," *Proc. of 8th ICSMFE*, Vol. 1, 185-190.

Jarquio, R. (1981). "Total lateral surcharge pressure due to strip load," *J. Geotech. Engg. Div., ASCE*, 107(10), 1424–1428.

Kim, J. S. and Barker, R. M. (2002). "Effect of live load surcharge on retaining walls and abutments," *J. Geotech. Geoenv. Engg.*, 128(10), 803-813.

Mueller Breslau, H. (1906). *Erddruck auf Stützmauern*. Kroener, Stuttgart, Germany.

Roscoe, K. H. (1970). "The influence of strains in soil mechanics," *Geotechnique*, 20(2), 129-170.

Nakai, T. (1985). Finite element computations for active and passive earth pressure problems of retaining wall, *Soils and Foundations*, 25(3), 98-112.

Sherif, M. A., Ishibashi, I., and Lee, C. D. (1982). "Earth pressure against rigid retaining walls," *J. Geotech. Engg. Div.*, ASCE, 108(5), 679-695.

Sherif, M. A., Fang, Y. S., and Sherif, R. I. (1984). "KA and K0 behind rotating and non-yielding walls," *J. of Geotech. Engg., ASCE,* 110(1), 41-56.

Shvetsov, G. I. (1974). "Earth pressures on retaining walls under the effect of a uniform load," *Gidrotekhnicheskoe Stroitel'stvo*, 5, 25-27.

Spangler, M. G. (1936). "The distribution of normal pressure on retaining wall due to a concentrated surface load," *Proc., of Int. Conf. Soil Mechs and Found. Engg.*, Graduate School of Engineering, Harvard University, 200-207.

Steenfelt, J. S., and Hansen, B. (1983). "Discussion of total lateral surcharge pressure due to strip load," *J. of Geotech. Engg., ASCE*, 109(2), 271–273.

Tawfiq, K. S. and Caliendo, J. A. (1993). "Laboratory investigation of polyethylene sheeting as a friction reducer in deep foundations," *Geotextiles and Geomembranes*, 12(8), 739-762.

Terzaghi, K. (1934). "Large retaining wall tests I- pressure of dry sand," *Engg. News Record*, 112, 136-140.

Terzaghi, K. (1936). "A fundamental fallacy in earth pressure computation, *J. of Boston Soc. of Civil Eng.*, 23, 71-88.

Vargin, M.N. (1968). "Effect of continuous surcharge on a retaining wall," *Fundamentry i Mechanika Gruntov*, 3, 8-10.

Wang, C. D. (2007). "Lateral force induced by rectangular surcharge loads on a cross-anisotropic backfill," *J. Geotech. Geoenv. Engg.,* ASCE, 133(10), 1259-1276.

Zhang, J. -M., Shamoto, Y. and Tokimatsu, K. (1998). "Evaluation of earth pressure under any lateral deformation," *Soils and Foundations*, 38(1), 15-33.