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Soil-Structure Interaction and Retaining walls: A Review Paper

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***Abstract:** This general report is prepared from the selected 32 papers of 19th ICSMGE 2017 which are in the area of soil structure interaction and retaining walls relevant to the ISSMGE Technical Committee TC 207. Research papers presented during the session of TC 207 – Soil-Structure Interaction and Retaining walls are from 22 member societies of ISSMGE, which cover Argentina (1), Brazil(1), Canada (1), China (1), Egypt (2), Hong Kong (1), Hungary (1), India (2), Iran (1), Japan (2), Kazakhstan (2), Korea (2), Mexico(1), Netherland (1), New Zealand (1), Romania (1), Russia (2), South East Asia (1), Syria (1), Tunisia (1), UK (4) and USA (2). Valuein parenthesis signifies number of papers from that particular member society. The research areas of these articles cover a various sub-themes namely (1) Laboratory Testing and Modeling (2) Small and Large Works (3) Natural Hazards (4) Environmental Preservation and Sustainable Development (5) Geotechnical Cultures and Responsibilities (6) Future Technological Innovation.*
***Keywords:** retaining wall, deep excavation, finite element method, in-situ measurements, numerical and analytical methods*

I. INTRODUCTION

With the increase in urbananization in the world number of buildings and structures are increasing. Which in turn led to the expansion of research and practice in the field of deep excavations and retaining walls in the framework of soil structure interaction. All the technical papers related to this research area can be grouped into major three categories, viz. (i) Instrumentation and field monitoring of retaining walls, (ii) analytical and numerical studies with the emphasis on soil-structure interaction (iii) laboratory model tests on retainingwalls. Papers received from twenty-two (22) member societies of ISSMGE with the current research and practice data relavent to soil-structure interaction and retaining walls will be immensely helpful for the researchers and practitioners worldwide.

II. REVIEW OF PAPERS

Abdelrahman et al. studied the behavior of narrow mechanically stabilized earth walls (ratio of wall width to wall height L/H < 0.7) using finite element software PLAXIS 8.2 and limit equilibrium based software Geo-Studio 2007. Two dimensional plane strain model was used in the finite element analysis. Hardening Soil model was chosen to simulate the nonlinear plastic response of soil. The reinforcements were modelled as line elements with a normal stiffness without considering any bending stiffness. An elastoplastic model was considered to model the breakage of reinforcement. Plate elements were selected to represent the stabilized and narrow MSE wall faces. In limit equilibrium modelling authors have selected Mohr-Coulomb soil model to represent backfill soil and reinforcement. The results obtained by the authors demonstrate that the factor of safety increases significantly withincreasing the aspect ratio, L/H, from 0.2 to 0.7 in the nonlinear relationship; where as it decreases significantly with increasing the spacing between reinforcing elements in a linear relationship. All predicted results showed that the failure surface goes partially through the reinforced soil and partially along the interface between the reinforced soil and stable face. It was also found that the inclination angle of the failure surfaceat any aspect ratio is less than the theoretical value defined by the Rankine failure surface.

Awwad and Kodsi conducted the numerical simulation todetermine the location of the neutral plane with Mohr – Coulomb and Modified Cam-Clay models. The case of a single pile driven in soft clay layer overlying a deep deposit of stiff clay was modelled using finite element program (PLAXIS V9.0). Then the proposed axisymmetric model was validated bycomparing its results with the results of full scale field test and numerical analysis available in the literature. The stressdistribution and settlements due to surcharge loading for Mohr Coulomb and Modified Cam-Clay models were also investigated. It was concluded by the authors that the location of the neutral plane gets deeper when the Mohr-Coulomb model is used. Also, modelling by using Mohr-Coulomb Model led to create a gap or interruption in the distribution of the negative skin friction when the type of the soil changed. As expected Mohr-Coulomb soil model could not show the relation between the stiffness and stress while the Modified Cam Clay did.

Balunaini et al. studied the effect of compaction stresses and surcharge loads on the performance of back-to-back reinforced soil retaining walls which are commonly used for the approach embankments of bridges and flyovers. The finite difference program, Fast Lagrangian Analysis of Continua (FLAC), was employed for the analysis (Itasca 2011). Back to- back walls of height 6m were considered. The length of reinforcement was 4.2 m. The foundation soil was assumed as rigid. Reinforced soil was simulated as homogenous, isotropic, elastic-perfectly plastic using Mohr-Coulomb failure criterion. Compaction stresses were applied at every stage over the surface of soil layer and the model was solved for equilibrium. Parametric study on effects of the stiffness of reinforcement and wall spacing to height (W/H= 1.4 and 2.0) ratios was carried out. The results at the end of reinforcement were reported in terms of Normalized lateral pressures for three cases: Case (a) without compaction stresses and surcharge, Case (b) with compaction stresses and no surcharge load, and Case (c) with compaction stresses and surcharge load. It was concluded by the authors that the lateral pressures at the end of reinforcement are bilinear for almost both the W/H ratios. Also, when the reinforcement stiffness and W/H ratio were low, surcharge induced lateral pressures decreases much faster with depth than that for the condition with high W/H ratio and reinforcement stiffness.

Bennett et al. described the use of integrated remote- sensing deformation monitoring and modelling for the assessment of levee section performance limit state. The modeled levee was part of the Whale's Mouth section on Sherman Island where satellite images and in-ground GPS sensors were used for displacement measurements. The finite element program was used to model the Sherman Island Levee section. The modeled soil profile consisted of 4 layers, which include a levee fill underlain by approximately 8 m of organic soil (peat). The levee was modeled using staged construction in 7 layers. Vertical displacements with time were reported. The Global Navigation Satellite System (GNSS) data showed an average of 0.13 m of deformation per year compared to the 0.095 m per year computed for point A (see Figure 1 of paper). The rates predicted by the model and measured for point B (see Figure 1 of paper) were not in good agreement, but the monitored points are located on the protected side of the levee. This paper showed that the combination of modeling and measurements will provide significantly more accurateinformation about the health state of levees than eithermodeling or measurements alone.

Brassai et al. presented the effects of local ground conditions on site response analysis results in Hungary. Authors have analyzed 1D response at six locations throughout Hungary using field data gathered for this purpose. Field measurements were captured using multi-channel analysis of surface waves (MASW) at the two locations in Győr and using seismic cone penetration testing (SCPT) at the other four locations (Tivadar, Szolnok, Kaposvár, Paks). The shear wave velocity profiles obtained from field measurements which are directly related to low amplitude shear modulus (Gmax) were applied to site response analysis. The method considered to select base motions was a magnitude scaling technique through software package REXEL. The program Strata was used to compute 1D response at the six sites. The results obtained in this paper showed consistently higher seismic actions compared to thestandard EC-8 soil type C spectra.

Do et al. discussed the chloride attack of reinforced earth retaining wall located in the frontal and wing walls of the abutments completed in 2002. From visual inspection of the reinforced retaining wall, authors concluded that the overall shape of the reinforced retaining wall was caused by the horizontal displacement of the soil layer caused by settlement ofthe embankment layer. Also, due to the partial breakage of the drainage channel installed at the upper part of the reinforced earth retaining wall, the loss of the retaining wall due to seepage erosion occurred. In order to evaluate the condition of reinforced earth retaining wall, authors referred to the detailed instructions of safety inspection and precise safety diagnosis (retaining wall) presented by Korea's Ministry of Land, Infrastructure and Transport (2012). The wall slope was 8.7 to 12.2% versus the planned linearity (-2%) at section 1 (see Fig10 of the paper). Section 1 was assessed as a dangerous condition that could lead to loss of structural stability due to the degree of slope. The maximum slope of the wall was 2.0 to4.3% as compared to the planned line (-2%) on section (2) [see Fig 10 of the paper].

Dorst and Vervoorn described a non-invasive method forquay wall reconstruction in historic inner cities. The proposednew non-invasive method did not require any excavation, dewatering or vibratory equipment. Also, it is safe and needs short time than traditional methods. The proposed method usesscrewed tubular piles forming a combined wall supported byrake piles at the waterside. The combined wall was installedbehind the old wall, on the land side, after which the old wall would be demolished. The proposed non-invasive technique employed in Krom Boomssloot was detailed. The stability, internal forces, and deflection of the quay wall for this casestudy were made using a 2D tool called D-Sheet Piling. The combined wall was modeled as an elasto-plastic beam on a foundation of uncoupled elasto-plastic springs, representing thesoil. During the quay wall renewal of the Krom Boomssloot, extensive monitoring of displacements was carried out. At the surface level on the land side of the quay wall, a maximum vertical settlement of 10 mm was measured. It can be observedthat the calculated settlements were significantly overestimated.

Fiegel and Derbidge described their approach and experience in developing and teaching a project-based learningactivity for an upper-division geotechnical engineering courseon earth retention systems. The student learning the soutcomes, outline of a lesson plan, and assignments for this project-basedlearning activity are detailed. An example problem statementand design constraints were also reported. The authors preparedthe project schedule as follows: research reinforced soil and MSE walls; participate during discussions on reinforced soil; receive project constraints and begin design; conduct strengthtests on backfill soil and wall materials; build and test the scalewall, and submit a report summarizing results. The exampleproblem statement mentioned was: A dual wall system should be designed to support sand within a plywood box.

The wallsconsist of poster board facing and brown wrapping paperreinforcement. Tape connects the reinforcement to the facing. The walls must support the weight of the backfill soil without significant deflection. The walls also need to support additional surcharge loads applied at the surface of the backfill. In addition,one wall must support a lateral load. It was learned that the project should be distributed early in the term to provide the students with sufficient time to research and structured laboratory activities helped the students to better understand the design constraints. Of the eight observed wall failures, half resulted due to poor construction. This provides a teachable moment for the instructor.

Gilmore and Fuentes were the first to implement the longestablished trial load method for design of arch dams to predict the behaviour of non-circular, curved-in-plan, deep excavations (retaining walls). In the trial load method, the wall was split into arch and cantilever sections. The deflections of each of the members are then calculated in isolation, adjusting the applied loading in an iterative manner until the displacements at points where the vertical and horizontal sections cross are the same. For the purpose of validation, authors modelled a retaining wall in London clay using PLAXIS 3D and obtained the displacement profiles along the depth of the wall. The displacements were in good agreement with the displacement profile resulted from trial load method. The location of maximum displacement by the both methods was at around 0.25-0.5 times the retained height along the centre of the retaining wall. This paper showed the successful application of the trial load method to predict the behaviour of curved walls and provided insights on further research to validate its usemore widely for design purposes and its potential to be applied to the design of typical retaining walls.

Gruzin studied the possibility of an increase in bearing capacity of driven piles of with increase in lateral surface of contact with ground. Variation of bearing capacity of the pile and specific load bearing capacity of the pile with pile lengthfor both square and equilateral triangle sections were reported. Comparison of cross-sectional areas corresponding to the triangular and square piles showed that at equal geometrical moment of inertia, the cross-sectional area of triangle section is smaller than a square section by 7.5%. Thus, this paper concludes that the manufacture of driven piles with a triangular cross section can reduce the material consumption by approximately 7.5%. It was also found that use of an equilateral triangle or a shortened hypocycloid instead of a square cross- section will increase the specific load-bearing capacity of the pile hanging drop by up to 14%.

Hardy et al. detailed the new holistic Observational Method (OM) framework described in Ciria C760 – the new revision to the Embedded Retaining Wall Design Guide. This new OM framework was described by four approaches: (i) Approach A – Ab initio optimistically proactive (ii) Approach B – Ab initio cautiously proactive (iii) Approach C - Ipso tempore proactive to make modifications (iv) Approach D - Ipso tempore reactive to make corrections. This method involves the determination of the most probable input soil parameters based on back analyses. These parameters would be used in an ab initio design to maximize saving in the wallthickness, toe embedment, and propping force. It is hoped that the clarity provided by Ciria C760 and the detailed explanations of this paper will encourage the use of the OM, particularly using the ab initio approach A.

Jahromi et al. investigated the route change method to guarantee energy transferring from production centers toconsumption locations by buried pipelines under earthquakeinduced landslides. In order to discover the mechanisms of damage occurrence and to rank possible routes, authorsperformed numerical modelling by ABAQUS program. The slope dynamic displacements and plastic strains under horizontal seismic excitations were obtained. The pipes intersected the slope by 90^o, were buried in 4 different positions. The 1^{st} one was considered in slope toe, the 2^{nd} and 3^{rd} ones were located in lower and upper slope part, also the 4^{th} position was considered in crest section respectively. It was observed from the results that the mid slope to upper parts were most hazardous zones for pipe passage. The lower slope pipe route was the 2nd risky zone for pipe passage. The numerical analysis was also shown that the crest and the toe part of the slope as the 3rd and 4th rank of dynamic displacements, therefore the pipes intersecting the slopes will be more secure if these two pipe routes were selected.

Kanoun et al. presented the design and follow up details of 12-20 m deep excavation and the installation of inclusions (nails) at Ariana City (Tunisia). The geotechnical investigation consisted of two boreholes and two pressuremeter tests carried out on the project site showed very stiff fissured marl extending to 30 m deep with no presence of water table. The lateral support system was a nailed wall which consists in nailing the top four meters of the excavation by 4 rows of HA32 rebars of 4 m length. The horizontal and vertical spacing between nails are 2 m and 1 m respectively. A plane strain model of the reinforced soil was built using the PLAXIS 2D software V9. Stage construction option including six phases was performed. The soil was assumed as Mohr-Coulomb material and the nails were modelled as an embedded beam. Recorded results from inclinometer measurements and pull-out tests were compared with the results of PLAXIS model. It was noticed that the horizontal displacements deduced from inclinometer measurements are not significant (few millimetres), whereas, the numerical analysis predicted 4.5 cm at the top of the wall. Back analysis showed that the Young's modulus' should be taken equal ten times the modulus obtained from the pressuremeter tests.

Maia conducted experimental research to understand the durability characteristics of geosynthetics. Four samples of polypropylene and polyester woven geotextiles which are separated into two lots were considered for the analysis. One lotwas exposed to the natural climatic conditions in Campos dos Goytacazes/RJ from August 2013 to August 2015. Another lot was degraded by accelerated UV test in the laboratory. To analyze the results, the author followed the procedure suggested by Dias Filho et al. (2016). It was observed from the results that the relation between the decrease in tensile strength and time is exponential.

Minh et al. discussed the development of a full-scale testing facility in Kazakhstan for interaction behavior of buried pipe and soil. It was developed at Nazarbayev University in Astana, Kazakhstan. The built testing rig for buried pipe-soil interaction consists of a large test chamber of 2x6x3.5m (WxLxH) effective dimensions to contain the buried test pipe segment under different backfill conditions; pulling forces on the pipe of up to 1000kN can be applied from both sides along the length of the chamber using electric load actuators to allow for load reversal. Authors have discussed one test example to demonstrate the performance of the testing facility. For the example test, the pipe was buried at 1.5m burial depth under a compacted sandy gravel backfill material. The measured moisture content was 4% and the initial pipe position before the test is at the offset distance equal to 138mm. The test was conducted in a displacement-controlled manner, which targeted a constant rate of 5mm/min. Force-displacement chart and vertical settlement profile were reported. It was observed that the downward settlement is less associated with horizontal movement than upward movement on the right side of the test chamber.

Nam et al. studied a new concept abutment (IPM) called Integrated and Pile-bented abutment separating the earth pressure by using mechanically stabilized earth wall (MSEW) which separates earth pressure from the abutment and makes less cross section and piles. The construction costs of Inverted T-Type and IPM Abutments were compared. The cost of the IPM abutment was $207,500, which accounted for 60% of the inverted T-type abutment cost of $345,000. Authors performed finite element analysis using MIDAS Civil 2012. The parametric study was aimed to figure out the effect of change in bridge length on the IPM abutment. It was found that the highest level of the bending moment acted on pile head was caused by the dry shrinkage, the temperature increase, and the temperature decrease.

Orabi et al. proposed the inverted U-Shape reinforced- concrete wall configuration that provides an alternative to gravity wall system in areas with limited base width. The proposed wall configuration consists of a stem embedded at the toe and extending to an optimized intermediate height, a relief floor acting as a tie-back, a dead-man, and a limited height gravity wall extending above the stem for the remaining wall height. Authors studied the performance of the proposed wall system in terms of global stability, induced straining actions, and wall movement. The parametric study was conducted using the 2-D finite element software PLAXIS and 2-D limit equilibrium (LE) analyses are also conducted using SLIDE software. The results showed that the critical failure surface is forming an active wedge against the dead-man, and a passive wedge against the stem with the surface intersecting both toes at points of high shear strains. It was observed that introducing the dead man resulted in up to 35 % reduction in horizontal deflections and up to 50% reduction in vertical settlements. The authors showed an alternative gravity wall system which showed a satisfactory performance of stability and serviceability.

Pender and Rodgers developed lateral-load deformation curves for timber poles embedded in Auckland stiff residual clay using finite element method. Three dimensional finite element modeling was conducted using the OpenSeesPL which is specifically developed for computations involving pile-soil interaction. Authors have used the term pole, rather than pile, because the concrete embedment ensures that the system behaves in an approximately rigid manner as distinct from a long pile which is flexible. The poles of pinus radiata were 250mm in diameter and the concrete embedment was 450 mm in diameter. The depth of embedment was in the range of 3 to 5 embedment diameters. The pole was assumed to be elastic. The saturated clay was modelled with the Pressure Independent Multi-yield surface material model in OpenSeesPL. The comparison of the computed lateral displacements of the three of the tested piles with the field measured displacement values was reported. The results showed that the lateral resistances calculated with OpenSeesPL were in good agreement measured displacement values. Design chart showing lateral displacements (for the embedded part of the pole) with depth for different lateral loads was proposed. It was concluded that the interface between the embedded pole and the surrounding soil must be close to smooth to obtain a good match between finite element calculations and the field data. Also, the calculated displaced shape of the embedded pole shaft indicates essentially rigid behaviour with a point of rotation towards the base of the embedded part.

Popa et al. investigated the effect of using various constitutive laws on displacements for numerical modeling of diaphragm wall. A 2D numerical modelling using finite element method (PLAXIS V8, 2D) for an anchored diaphragm wall for a deep excavation was analysed using following soil constitutive laws: Mohr – Coulomb Model, Hardening Soil Model and Hardening Soil Model with Small Strain Stiffness. The modeled retaining wall was built in Bucharest, Romania for a deep excavation of 66 x 127 m and a maximum depth of over 16 m. The retaining structure consisted of diaphragm walls 80 cm thick and 20 – 24 m long. Numerical results were validated with the inclinometric measurements. The major conclusions drawn by the authors are: (i) wall and ground displacements determined using Mohr-Coulomb criterion are exaggerated and even the shape of the deformation curve is not realistic (ii) computations using Hardening Soil criterion indicated a substantial improvement of results. Even if displacements are still high, it can be observed that the wall deformation shape is closer to the measured one (iii) the results obtained using the Hardening Soil Model with Small Strain Stiffness are close to the field

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measurements. However, the input model parameters required dynamic laboratory or in situ tests.

Rigby et al. detailed the challenges and benefits of using proprietary lightweight aggregate (LWA) fill, Leca® LWA, in combination with a specific proprietary geogrid, tensar high density polyethylene (HDPE) uniaxial geogrids. This paper described the use of the same combination light weight reinforced soil retaining wall system adopted for the design and construction of two approach embankments to a new bridge to carry the new Finningley And Rossington Regeneration Route Scheme (FARRRS) highway over the existing East Coast Main Rail Line. In total there were 6No. mechanically stabilised earth (MSE) retaining wall type structures forming the 2No. approach embankments to the new bridge. The 2No. approach embankments either side of the bridge were formed with near vertical sides (i.e. 4o slope from vertical) MSE back-to-back modular concrete facing block walls rising to a maximum height of 12.8m and 12.5m respectively. The chosen embankment fill material [Leca® LWA i.e., (LLWA)] is an expanded, lightweight clay granular ceramic material. It was observed from the external stability calculations that due to the low density of the LWA, the reinforcement lengths required to achieve target factor of safety for sliding are higher than the routine length of 70% of the mechanical height of the structure that is normally expected when naturally sourced granular fill material is used. Also, because of the low bulk density of the LWA, bearing capacity factors of safety are easily met and the middle third rule is equally satisfied.

Rivera et al. investigated the problem of soil-pile interaction under seismic transverse lateral loads on soft soil in the case of Mexico City. A case of pile rows is considered and solved by generalizing the methodology developed by Professor Zeevaert (1980, 1983), which considers the soil as a continuous medium and the pile as a beam resting on interacting springs. It was assumed that under seismic transverse lateral loads, the base shear is not distributed equally between the total numbers of piles, but in the row of piles located transversely to the horizontal seismic force, there is an interaction. In order to illustrate proposed methodology a foundation with a set of six friction piles, of square section 40x40 cm, joined in their head by a foundation rigid slab was adopted. Results were validated by comparing them with the results of the analysis proposed by Zeevaert (1973, 1980) for an individual pile. Relative displacements, bending moment and shear force diagrams derived from the reactions forces were reported. Finally, this paper recommends comparing analytical results derived from this methodology with field measurements to validate proposed method.

Sawamura et al. investigated the dynamic behavior of two-hinge precast arch culvert during strong ground motion experimentally. 1/5 scale shaking table tests were conducted using the Strong Earthquake Response Simulator (SERS) at the Disaster Prevention Research Institute (DPRI), Kyoto University. The culvert model was made from reinforced concrete. Both the foundation soil and the backfill were made from Edosaki sand. Three different earthquake ground motions were applied. Level 1 and Level 2 earthquake motions (Japan Road Association, 2012) which are used to design bridges in Japan were input in Step 1 and Step 2. Further, a 1 Hz tapered sine wave was input to investigate the damage morphology of the culvert after large seismic waves. It was concluded that the possibility for the whole culvert to collapse due to the dislocation of a hinge part is low even when the shear strain of the ground is more than 6%.

Shahin et al. conducted finite element analyses of anchor type retaining wall in the braced excavation. First, the authors have conducted some model tests using the mass of aluminum rods as model ground. The size of the model ground was 680mm in width and 450mm in height. The retaining wall was 300mm in length, 60mm in width and 0.5mm in thickness, which was a plate of aluminum material. Using the results obtained from the model tests, authors have validated their own finite element code called FEMtij-2D. The FEMtij-2D uses an elastoplastic constitutive model called the subloading *tij* model. After the validation, authors have simulated a field observation of an anchor type retaining wall by finite element code. The results obtained by the FEMtij-2D and field observed values were in good agreement. It was concluded that longer anchor in the lower parts of the excavation produces a significant supporting effect resisting wall displacement of the backfill ground. Also, it was observed that the supporting effect of the anchor in braced excavation can be achieved, if the anchor block is setup outside the assumed slip surface developed during excavation.

Shulyatiev et al. detailed the geotechnical aspects of the Moscow Luzhniki stadium reconstruction. The change in the stress-strain states of the stadium base taking into account anthropogenic and historical over compaction of the soil, and a sequential dismantling of the old stands and construction of the new ones, consolidation of the clay soils both in course of the construction activities and after construction completion were reported. In the first stage of the calculations, authors determined the parameters required for mathematical modelling of changes in the stress-strained conditions of the soil body due to the construction activities. PLAXIS software with Hardening Soil (HS) model was employed. In the second stage, a multi- step verification on the grounds of numerical modelling of the in-lab and field soil tests with their further juxtaposition with test data was conducted. In the third stage, a 3D-environment was used to proceed with the control verification calculations for the base and foundations to examine the influence of the reconstruction activities. It was found that the ultimate foundation displacement values of the sections were less than 5cm. The mean design displacement reached 2 - 3 cm. At that, the admissible ultimate displacement was 15 cm.

Srivastava and Malhotra studied the influence of existing nearby tunnel on frictional resistance of single pile capacity in cohesionless soil numerically, using commercially available finite element tool PLAXIS-2D. The finite element analysis was performed in two stages: (i) without underground conduit or tunnel (ii) with underground conduit or tunnel. The percentage reduction in the pile capacity due to the sexistence of underground conduit or tunnel in the vicinity of the pile shaft was estimated using the load settlement curves obtained for both the cases. FEM analysis showed that the zone of influence increases with increase in the relative stiffness (Ec/Es), [Ec = the modulus of elasticity of the pipe material and Es = the modulus of elasticity of the soil within zone of influence] and this results in a higher reduction in the pile capacity. It was observed that the reduction in the pile capacity ranges from 5% to 20% and it follows a certain trend. Also, with an increase in the diameter ofthe pile, the % reduction in the pile capacity is increasing.Based on the results of the numerical analysis, the analytical solution was proposed to estimate the reduction in the frictional capacity of a single pile to be installed in cohesionless soil. Design charts were prepared to directly read the reduction in the friction capacity of the pile based on different design parameters, such as tunnel or buried pipe diameter, length and diameter of the pile, geotechnical properties of sand, the relativestiffness of pile material with respect to the surrounding soil within the zone of influence.

Suryasentana et al. proposed a new approach for computing stiffness values for a rigid, rough circular surface footing bearing on a multi-layered non-homogeneous elastichalf space. In the proposed simplified methodology the multi- layered problem was modelled by equivalent weighted average elastic parameters. The novelty of this work is the generalisation to the solutions of Doherty et al. (2005) to account for layering in the half-space. In the proposed approach authors have used the two-parameter Weibull distribution function as the weighting function and calculated the vertical stiffness, lateral stiffness, rotational stiffness, torsional stiffness and a cross-coupling stiffness between horizontal and moment loading. The predictions using the calibrated Weibull weighting functions were validated against the original Doherty et al. (2005) solutions. Design charts showing weighting functions for different loading types were reported. It was observed that the zone of influence of vertical loading can extend to a depth of three diameters, while the zone of influencefor non-vertical loading stops at a depth of one diameter. Authors have also conducted the numerical study using three- dimensional finite element analyses using the 3D FE software, ABAQUS v6.13. Comparison of dimensionless stiffness predictions by the proposed model and the solutions of Doherty et al. (2005) against the benchmark 3D FE results showed a good agreement. However, for cases with stiff layers over softerlayers the proposed model overestimating the stiffness.

Ulitsky et al. described the numerical simulation of two case histories by taking into account their deformation scheme. The Authors developed the soil-structure interaction approach (the core of this approach is the procedure of joint-up calculations of superstructure, foundations, and subsoil) that can account for deformability. The computations were performed by software complex FEM Models 2.0 developed by the authors.The advantage of this approach was there is no need to perform separate calculations of structural elements, foundations, and subsoil. The two case histories chosen are (i) reconstruction of large Menshikov Palace in a suburb of St. Petersburg (ii) provision of underground space under the newly constructed 9- storied residential building in the centre of St. Petersburg. From the modelling of case history (i) it was found that there is a danger of retaining walls failure exclusively on Japan pavilion. From the simulation of case history (ii) it was observed that the computed horizontal displacements of the pit walls do not exceed 4 cm during the trench excavation with one level of struts and 2 cm – with two levels of struts. This paper showed that the application of Soil-Structure Interaction gives a very reasonable estimation of behavior of structures with the account of soil strength and deformability.

Vincent presented the performance of two different deep excavation methodologies in similar ground conditions. The sites of similar ground conditions considered are Santiago and Lima. The typical retaining wall system that was used to execute deep excavations (up to 30m) in Santiago is a discontinuous wall consisting of reinforced concrete piles (either hand-excavated or drilled), laterally braced by ground anchors. Whereas in Lima it was an anchored wall consisting ofthe reinforced concrete wall of the building laterally braced with several rows of ground anchors. Author has explained the various instrumentation details, measured horizontal deformations and measured ground anchor loads in the sites Parque Oriente Building, Office Building in Santiago and Lima respectively. It was found that the mean geomechanical behaviour of both geological formations was better than expected, based on published data.

Wang and Xu investigated the strength and stiffness parametersof hardening soil small strain model (HSS) of Shanghai clay. To derive soil parameters of HS model, oedometer tests, consolidated undrained and drained triaxial tests and consolidated drained loading-unloading-reloading triaxial tests were conducted. Shear stiffness at small strains was investigated in the laboratory using a resonant column apparatus equipped with bender elements. Authors established a complete stiffness degradation curve by combining the results of both bender element tests and resonant column tests. A correlation between stiffness parameters which is applicable to Shanghai clay was proposed. An empirical equation between small strain stiffness and stress states was also proposed. Authors have conducted three-dimensional finite element analysis using the obtained HSS parameters on a deep excavation adjacent to existing buildings using PLAXIS (PLAXIS, 2015). The comparison of finite element analysisresults and field monitoring data showed a fairly goodagreement.

Yang et al. studied the earth pressure coefficients (K) along the vertical centerline (VCL) in mine stopes numerically. Authors have used FLAC software to evaluate the stress state ofcohesionless backfill and the resultant *K* value along VCL, considering independent and related values of the Poisson's ratio *v* and internal friction angle < ' of the backfill. The backfillis modeled as Mohr Coulomb elasto-plastic material. It was found from the results that the *K* value agrees well with the at- rest coefficient *K0* when *v* and < ' are linked. When the value of *v* is independent of < ', it may approach *Ka* (an active state) for small *v* values. However, for large *v* values, *K* value agrees wellwith *K0* even in the case of *v* and < ' are independent. Authors also observed that near the walls, the vertical stresses obtained with interface elements may be over predicted compared to those obtained without interfaces, while the horizontal stresses remain similar.

Zea et al. proposed a methodology to assess the interaction of soil-wall using Zeevaert's soil-structure interaction method (1983), which considers the soil as a continuous medium and the wall as a framework of beamsresting on interacting springs. The proposed methodology considers the different stages of the construction process and can be applied to either anchored or shoring system. Anchor (or shoring) was considered as an elastic bearing. Modeling of the wall was achieved by transforming it into a mesh or grid of bars with equivalent properties to the actual foundation. Compatibility of deformations in soil-wall interface was established to determine displacements and distribution of reactions. To obtain the influences in the horizontal direction, authors have used the fundamental Mindlin's solution for horizontal point load assuming the soil has a linear elastic behaviour. The proposed methodology was applied to a soft soil excavation site in Mexico City, formed by an anchored wall cast-in-place. The results were reported in terms of horizontal displacements for each stage of construction. The analysis results were in good agreement with the field measured displacement values.

Zhou and Ng developed a new thermo-mechanical modelby using the bounding surface plasticity theory for unsaturated soils. Unlike the conventional elastoplastic models, the proposed model allows the plastic strain inside the bounding surface for capturing the degradation of soil stiffness with strain. Thermal, hydraulic and mechanical behaviour of unsaturated soil were modelled through a fully coupled approach. Authors proposed some new formulations incorporating the effects of suction and temperature in different components of the proposed model. The proposed model was applied to simulate triaxial tests on compacted silt to predict the small strain behaviour at various suctions and temperatures. Measured and computed results are compared and analysed. It was found from measured results that the deviator stress increases non-linearly as shear strain increases, even at very low deviator stress. Such a non-linearity at small strains was predicted well by the proposed model.

III. SUMMARY

A proper understanding of the soil-structure interaction plays a key role in the efficient design of geotechnical structures. This general report of (Soil-Structure Interaction and Retaining Walls) summarizes the various recent developmentsin research and practice in the area of soil-structure interaction and retaining walls. The subjects of these papers cover a variety of sub-themes like deep excavations, analytical and numerical analyses on retaining walls, experimental research on geosynthetics, model studies on mechanically stabilized earth retaining walls, material modelsin numerical analyses, case histories of soil-structure interaction etc. Future scope of research and development of practice in the area of soil-structure interaction and retaining walls can also be obtained from the present paper.

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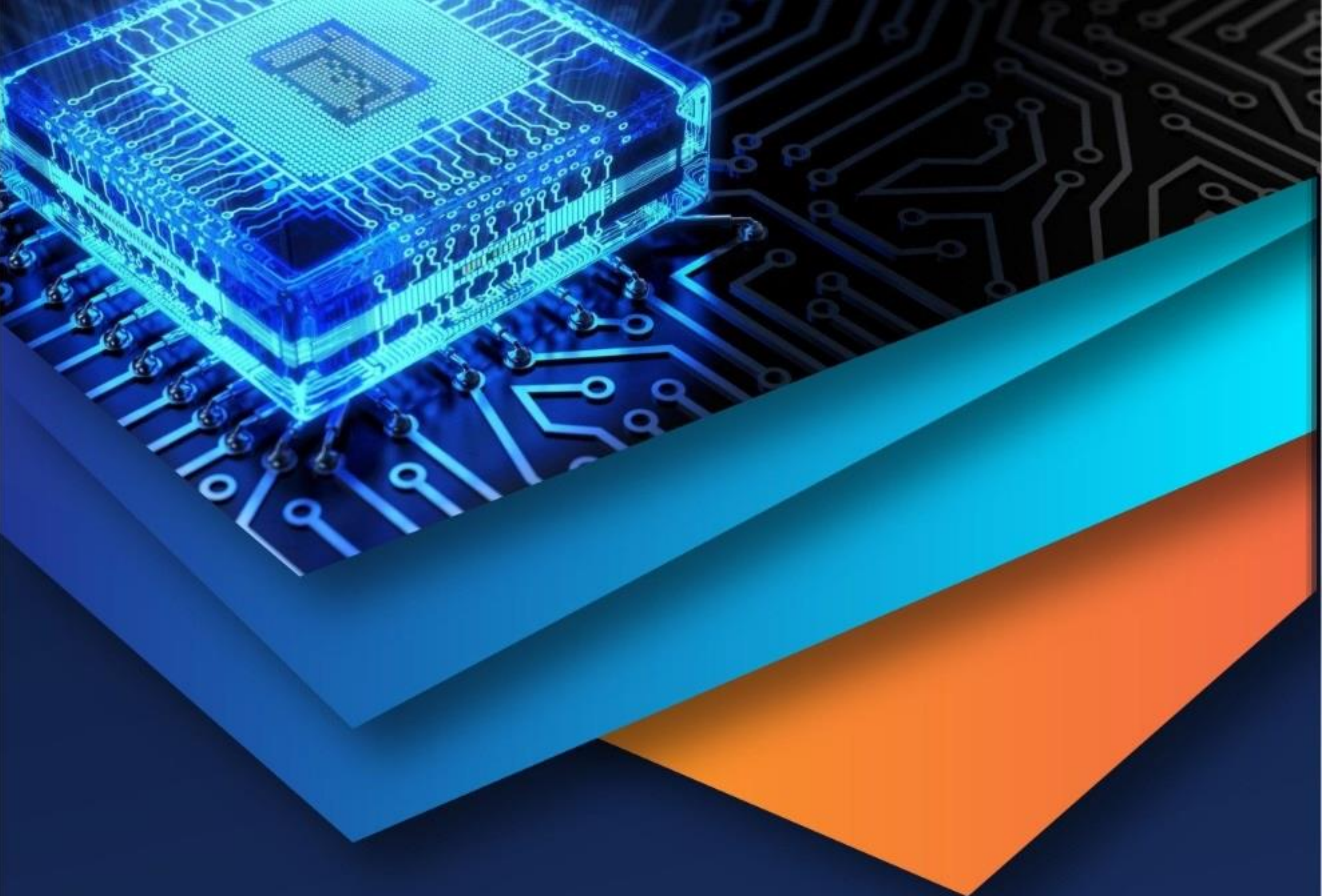

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