15 Aug 2008, 11:05am - 11:35am

General Report — Session 5: Case Histories and Failure of Retaining Structures, Slurry Walls, and Deep Foundations

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Recommended Citation

Sy, Alex; Wu, Yingwei (Alex); and e Silva, Jose Matos, "General Report — Session 5: Case Histories and Failure of Retaining Structures, Slurry Walls, and Deep Foundations" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 5.
https://scholarsmine.mst.edu/icchge/6icchge/session00c/5

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

CASE HISTORIES AND FAILURE OF RETAINING STRUCTURES, SLURRY WALLS, AND DEEP FOUNDATIONS

GENERAL REPORTER
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General Report – Session 5

INTRODUCTION

This General Report covers papers submitted to Session 5 on Case Histories and Failure of Retaining Structures, Slurry Walls and Deep Foundations. The Report is presented in the following three sections: (1) overview of the topic; (2) review of submitted papers; and (3) final comments.

OVERVIEW OF TOPIC

Earth retaining wall systems have been developing rapidly in the last 30 years, driven largely by the need for excavation or fill support for construction of buildings, transportation infrastructure and utilities in urban environments, advances in construction equipment, and development of new materials.

Earth retaining systems can be conveniently classified according to construction methods, i.e. fill wall construction, in which the wall is constructed from the base to the top ("bottom-up"), and cut wall construction, in which the wall is constructed from the top of the wall to the base ("top-down") (FHWA, 1997). Typical types of walls under each category are:

1. <u>Fill Wall Construction ("Bottom-Up" Construction)</u>

   A. Rigid Gravity and Semi-Gravity Walls
      - Cast-in-place concrete gravity wall
      - Cast-in-place cantilever/counterfort wall

   B. Prefabricated Modular Gravity Walls
      - Crib wall
      - Bin Wall
      - Gabion Wall

   C. Mechanically Stabilized Earth Walls or Reinforced Soil Slopes

2. <u>Cut Wall Construction ("Top-Down" Construction)</u>

   A. Non-Gravity Cantilevered Walls
      - Sheet pile wall
      - Soldier pile and lagging wall
      - Slurry (diaphragm) wall
      - Tangent/secant pile wall
      - Soil mixed wall

   B. Anchored Walls
      - Grouted anchor (tieback)
      - Deadman anchor

   C. In-Situ Reinforced Walls
      - Soil-nailed wall
      - Micropile wall

The above earth retaining systems are technically feasible for both temporary and permanent applications. Selection of the most appropriate system depends on many factors, including site constraints, project-specific wall performance requirements, wall system geometry, constructability considerations, availability of equipment and materials, durability, cost, aesthetic requirements and environmental issues.

Many projects employ more than one retaining wall systems in an excavation to suit the site, geologic and project requirements. Hybrid systems combining some of the above earth retention systems are also used. In some cases, walls conventionally used for excavation support are also used for fill support, for example, sheet pile walls in coastal areas to create fill platforms, or double sheet pile walls with horizontal cross ties and infilled with lightweight materials to form bridge approaches on soft ground.

REVIEW OF PAPERS

Twenty nine (29) papers were submitted to Session 5. Table 1 lists a summary of the papers submitted and reviewed for this Report. The papers are listed in Table 1 in order of their assigned paper numbers, and are divided according to their applications as stated in the case histories, namely:

1) Buildings (10 papers);
2) Transportation (12 papers);
3) Dams (4 papers); and
4) Miscellaneous (3 papers).

The 10 papers related to buildings or structures covered the whole spectrum of earth retaining systems available for excavation support.

The 12 papers related to transportation facilities also covered a wide range of retention systems for both fill wall construction and cut wall construction.

Of the 4 case histories on dams or dikes, three involved slurry trench walls, i.e. cement-bentonite, plastic concrete and concrete diaphragm walls, and one discussed groundwater control for a dam foundation excavation.

The 3 miscellaneous papers dealt with deep mixing ground treatment for liquefaction mitigation, Trench Remixing and Deep Wall Method of in-situ soil mixing for installing vertical barriers, and an experimental physical model test program to investigate passive pressures on retaining wall.

The papers under each application topic are briefly summarized and their conclusions discussed following Table 1.

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Table 1. Summary of Papers in Session 5

Paper No.	Authors	Paper Title	Building	Transp-ortation	Dams	Misc.
5.01	Kumars Zand-Parsa (USA) Kamran Zand-Parsa (Iran)	The Simplified KZP5 Method for Soil Nail Design in Granular Soils		X		
5.02	Kumars Zand-Parsa (USA) Kamran Zand-Parsa (Iran)	Stability of a MSE Wall Under Bridge Falsework Bent Surcharge		X		
5.03	Raj Siddharthan Ali Porbaha (USA)	Seismic Response Validation of DM Treated Liquefiable Soils				X
5.04	Javad Safadoust Gholam Moradi (Iran)	Numerical Analysis of Algonquin Geogrid Reinforced Soil Retaining Wall under Construction and Earthquake Loading		X		
5.07	Shaw-Shong Liew Chee-Min Khoo (Malaysia)	Lessons Learned from Two Investigation Cases of Ground Distresses due to Deep Excavation in Filled Ground	X			
5.08	Shahriyar Mojahed Mark French (USA)	The Selection of an Earth Retention System at the Boston's Central Artery/Tunnel Project		X		
5.10	Jan Masopust (Czech Republic)	Reconstruction of Pier Foundations of the Charles Bridge in Prague		X		
5.11	J. Matos e Silva (Portugal)	Behaviour Monitorization of a 13 m High Gabions Walls		X		
5.12	J.Jai J.H. Wang C.P. Liu L. L. Zhang X.L. Xie (China)	Behavior of an Excavation Adjacent to a Historical Building and Metro Tunnels in Shanghai Soft Clays	X			
5.13	Bon Lien Jesus Gomez Chris Bailey (USA)	Design and Construction of Anchored Flexible Facing Excavation Support and Soldier Pile Wall		X		
5.15	H.B. Keskin H.T. Durgunoglu S. Ikis (Istanbul)	Harmony of Retaining Systems to Various Local Subsoil Conditions - A Case Study	X			
5.16	Dimitrios Konstantakos (USA)	Online Database of Deep Excavation Prediction & Performance	X			
5.17	P. Becker B. Gebreselassie H.-G. Kempfert (Germany)	Back Analysis of a Deep Excavation in Soft Lacustrine Clay	X			
5.19	Xiaohai Wang Francois G. Bernardeau Jean-Claude Younan (USA)	Slurry Wall Stability Analysis - Constructing Cement-Bentonite Slurry Trench Adjacent to Exiting Soil-Bentonite Backfill			X	
5.20	Abdolreza Osouli Youssef Hashash (USA)	Learning of Soil Behavior from Measured Response of a Full Scale Test Wall in Sandy Soil	X			

Paper No.	Authors	Paper Title	Building	Transp-ortation	Dams	Misc.
5.21	Jeffrey C. Evans (USA)	Alamitos Gap: A Case Study using the Trench Remixing and Deep Wall Method				**X**
5.22	Salah Sadek (Lebanon)	Failure of a Hybrid Flexible Shoring System for a 30M Excavation: Exploration of Causes and Remedial Measures	**X**			
5.23	Sami Arsoy (Turkey)	Analysis of a Group of Failing Retaining Walls and Remediation Measures		**X**		
5.25	Wolfgang Roth Bei Su Jake Vanbaarsel Eric Lindquist (USA)	Effect of High In-Situ Stress on a Braced Excavation		**X**		
5.26	Li Yan D.A. Trapp Alex Sy (Canada)	Construction of a Plastic Concrete Seepage Cutoff Wall for the New Coquitlam Dam			**X**	
5.29	Ravinda Gill Mahavir Bidasaria (India)	Anchored RCC Diaphragm Wall Coffer Dam for Bisalpur Dam (A Case - Study)			**X**	
5.30	Luljeta Bozo (Albania)	Failure of Retaining Structures in Lezha and their Consequence in near Establish Building	**X**			
5.31	Fabio Matta Antonio Nanni (USA)	Response of FRP Reinforced Concrete Softeyes for Tunnel Excavation		**X**		
5.33	A. Hadi Suroor Mahi Galagoda Chris Caldwell (USA)	Design and Construction of Circular Secant Pile Walls in Soft Clays	**X**			
5.34	Richard Kulesza (USA) Nikos Boussoulas (Greece) Allen Marr (USA)	Deep Excavation in Hard Sandy Clays for Stations and Shafts of the Athens Metro Stavros Extension		**X**		
5.35	Petr Koudelka (Czech Republic)	Granular Mass Behaviour under Passive Pressure				**X**
5.36	P. Jagannatha Rao K. Srinivas (India)	Practical Lessons from the Failure of a Reinforced Soil Retaining Wall on a Major Highway		**X**		
5.37	AmirHosein Sadeghpour Ali Ghanbari Meysam Fadaee (Iran)	Groundwater Lowering in Deep Excavation (Case Study: Foundation Excavation of Shahid Madani Dam)			**X**	
5.40	Satyendra Mittal Meenal Gosavi Swami Saran (India)	Stabilization of Gantry Column Foundation by Soil Nailing	**X**			

Buildings

Paper No. 5.07 by Liew, S.S. and Khoo, C.M. presented two case histories of unanticipated ground distress during deep basement excavations for building construction in Malaysia. In each case, significant tension cracks and ground subsidence were manifested on adjacent property during excavation. The paper described the subsequent site investigation, remedial design, and construction monitoring employed at each site to successfully complete the excavation. At both sites, deep uncontrolled fills placed over compressible native soils and perched groundwater levels were found to be the cause of the ground distress. In Case History A, a soil nailed shotcrete wall, in combination with an anchored sheet pile wall at the lower elevation, was used to stabilize the 14.5 m deep excavation. In Case History B, in which the initial temporary retaining wall had moved out by up to 1.2 m, a sheet pile wall system with internal strutting and staged excavation was used to stabilize the 10.5 m deep excavation. Finite element analysis using Plaxis was used in both cases to analyze the failure mechanism and provide confidence in the remedial solutions. Lessons learned from the case histories were summarized.

The authors have documented two interesting case histories of basement excavations in filled ground that resulted in ground distress to adjacent property. At both sites, the effects of uncontrolled fill placed on soft deposits in former “valleys” were not detected and considered during design, resulting in construction delay and costly remediation. The authors highlighted the importance of reviewing original or pre-development topography during design, and the use of instrumentations for excavation construction monitoring.

Paper No. 5.12 by Jia, J., Wang, J.H., Liu, C.P., Zhang, L.L. and Xie, X.L. described the deep excavation for construction of the New Yi Bai Commercial Center in Shanghai, China. The site is underlain by soft clays. The deep excavation is located adjacent to an existing historical building supported on wooden piles on the south side, and existing underground utility and metro tunnels on the west side**.** The retaining wall system consisted of a diaphragm wall constructed prior to excavation, and mutli-level horizontal struts installed in stages as excavation proceeded. At the south side where the excavation was up to 18.7 m deep, the diaphragm wall was a 1.2 m thick combined deep soil mixed wall and jet grout wall. At the west side where the excavation was 15.9 m deep, the wall was a 1.0 m thick soil mixed wall. Prior to construction, two-dimensional finite element modelling soil-structure interaction analyses of the excavation were performed to predict deformations of adjacent structures and to check against allowable movement criteria. A comprehensive instrumentation program that included inclinometers in the wall and soil, earth pressure cells on the wall, and piezometers was implemented during construction. The field monitoring results confirmed the satisfactory performance of the wall.

The authors have presented an excellent case history of using finite element modelling in design to predict the effects of excavation on adjacent structures, and using appropriate instrumentations during construction to confirm retaining wall performance. The observed inclinometer, total lateral earth pressure and pore-water pressure data provided great insights into the diaphragm wall behaviour during construction in soft clay.

Paper No. 5.15 by Keskin, H.B., Durgunoglu, H.T. and Ikiz, S. described the retaining wall systems used for construction of the massive BJK Fulya Complex in Istanbul, Turkey. The 29,000 m^2 area development included high-rise twin residential towers, hospital, and hotel, as well as shopping mall and entertainment facilities, and with 4 to 5 underground levels. The site was located on the side slope of a former creek that had been filled to form the main road adjacent to the development. The sloping site topography required deep excavations varying in height from 18.5 m at the lower (road) level to as much as 36 m on the uphill side. The site was underlain by variable deposits of loose alluvium and fill overlying greywacke bedrock formation with various degrees of weathering and fracturing. The complicated geology and high seismicity of the site necessitated the use of five different retaining wall systems around the 690 m perimeter of the excavation to suit ground and groundwater conditions. The retaining walls included permanent and temporary soil nailed walls, permanent tied-back cast-in-situ reinforced concrete wall, and temporary tied-back diaphragm wall consisting of bored concrete soldier piles with intermediate jet grout columns. Inclinometers were installed prior to construction to monitor ground movements behind the walls during excavation. The inclinometer monitoring results indicated maximum horizontal displacements relative to wall height of 0.1 to 0.2%, which were below the 0.3% allowable in the contract.

The authors have documented an interesting case history of a large excavation that employed different retaining wall systems to suit variable ground and groundwater conditions around the perimeter of the deep excavation, with heights varying from 18.5 m to 36 m. Extensive inclinometers were used to monitor lateral wall displacements during construction and to confirm the satisfactory performance of the retaining walls.

Paper No. 5.16 by Konstantakos, D.C. described an online database of deep excavation performance and prediction recently developed by the author. At its current state, the searchable database comprises 39 case studies of mostly diaphragm wall projects in the U.S. The main characteristics of the 39 projects are summarized in the paper, including soil types, wall and support types, excavation depths, and measured maximum horizontal and vertical movements. Typical recorded inclinometer wall displacements for different types of walls are presented and discussed. The author has benchmarked or backanalyzed some of the case studies where sufficient information exist, using the Deep and Plaxis finite element programs. The benchmarking results are summarized in the paper, and presented in a plot of maximum observed wall displacement to excavation height ratio versus calculated basal stability safety factor.

The author has developed a useful online searchable database to allow deep excavation performance data to be readily accessible to engineers. The current database consists of 39 excavation projects. The author intends to expand the database, and encourages other engineers and companies to contribute to this effort.

Paper No. 5.17 by Becker, P., Gebreselassie, B. and Kempfert, H.G. presented a backanalysis of the deep excavation in soft lacustrine clay for the LAGO Shopping Center in Constance, Germany. The trapezoidal shaped excavation was 100 m long and 50 m to 100 m wide, with one section up to 9.9 m deep, and another section up to 8.0 m deep. Sheet pile walls were used to shore the excavation, but the deeper section was further partitioned with sheet pile walls into three longitudinal strips. End bearing deep bored piles were installed to support the structure, prior to excavation. The excavation was carried out in small blocks progressively in sequence with strut installations. Construction performance monitoring with inclinometers, piezometers, and survey monuments was conducted. Backanalysis of the detailed excavation sequencing, including soil-structure interaction and soil consolidation effect, was carried out using the 2D Plaxis program. The numerical analysis, with 36 modelled construction stages, gave encouraging results compared to measured wall deflections, foundation pore pressures, and ground movements.

This case history highlighted the importance of modelling actual construction stages in appropriate time steps in numerical analysis in order to produce results in good agreement with observed performance data. The authors further indicated that material input parameters for soft clay should be obtained from carefully conducted triaxial tests and local experience.

Paper No. 5.20 by Osouli, A. and Hashash, Y.M.A. described the application of the SelfSim inverse analysis approach to extract soil behaviour from measured excavation performance data. The authors analyzed a full scale instrumented solder pile and lagging research wall in sandy soil at Texas A&M University. Half of the instrumented 7.5 m high wall had two levels of tiebacks, and the other half had one level of tiebacks. The soil behavior in the two-level tieback section was extracted using wall deflection, inclinometer and tieback load measurements through the inverse analysis, and the results then used to predict the excavation behaviour in the one-level tieback wall section.

Although the inverse analysis appeared to show some promise, the results had no correlation to conventional soil parameters. The authors acknowledged that ongoing research is focusing on understanding the extracted soil behaviour and its relation to known soil properties.

Paper No. 5.22 by Sadek, S. described the investigation of a failed tieback retaining wall during excavation for a large high rise development in Beirut, Lebanon. The hybrid flexible shoring system consisted of prestressed active anchors in the upper part of the excavation and passive nails in the lower part, with reinforced shotcrete facing. The excavation was up to 30 m below street level. During excavation, significant displacements occurred over a 100 m long section when the depth of excavation reached 28 m, resulting in longitudinal cracks on a major road up to 20 m away from the excavation. Post-failure site investigation and limit equilibrium stability and finite element method analyses were carried out to evaluate the cause of the deep-seated failure in soil overlying weak marl and limestone. The failure investigation concluded that the initial shoring design was deficient. Analysis of observed wall deformation data also indicated influence of precipitation on movement. The remedial solution adopted and successfully completed was an anchored contiguous cast-in-situ reinforced concrete pile wall.

The author cautioned the use of flexible tieback shoring system for deep excavations in complex geologic conditions.

Paper No. 5.30 by Bozo, L. presented an investigation of the failure of two concrete retaining walls constructed adjacent to two 8-storey buildings in Lezha, Albania. The existing buildings were supported on mat foundations on saturated fine sand and silty sand. The two cantilever concrete retaining walls displaced by rotation during excavation, resulting in differential settlement of the building foundations. The remedial solutions appeared to consist of deeper piled wall and internally braced sheet pile wall.

Unfortunately, the paper is difficult to comprehend.

Paper No. 5.33 by Suroor, H., Galagoda, M and McGhee, C. described the design and construction aspects of two circular Liquefied Natural Gas (LNG) impoundment basins in deep soft clays in Texas Gulf coast near the Louisiana/Texas border. The 60 ft diameter circular basin was 32 ft below grade and the excavation was retained permanently by concrete overlapping secant pile wall. Excavation stability and base heave were the main concerns during excavation. During design, detailed axi-symmetric finite element analysis (FEA) using PLAXIS was used for deformation and stability analyses, and verified by limit equilibrium stability analyses for circular excavations. Input parameters were obtained from field and laboratory tests, and from backanalysis of the performance of a nearby test dike. The FEA was used to predict excavation base heave, wall movement and forces. The FEA results indicated negligible shear and bending moments in the wall, confirming that the circular wall, as expected, was essentially in compression from axial and hoop forces. Construction of the secant pile wall was briefly discussed.

Although no construction performance data were available, the authors have demonstrated that carefully conducted finite element analysis, with checks against limit equilibrium analysis and other simple solutions, can be used effectively to predict wall stresses, deformation, and base stability for LNG impoundment basins in soft clays.

Paper No. 5.40 by Gosavi, M., Mittal, S. and Saran, S. presented a case history of the stabilization of gantry crane column footings by soil nailing in Ludhiana, India. A 6.3 m deep excavation in sand was required inside an existing industrial building to install a High Performance Hydrogen Annealing plant. The excavation was immediately adjacent to, and extended 3.3 m below, the foundations of two heavily loaded gantry crane columns. During excavation, the soil beneath the column foundations was stabilized with 2.4 m long horizontally driven soil nails, at vertical and horizontal spacing of 0.3 m, and with shotcrete.

This paper illustrates an effective method of stabilization of vertical excavations adjacent to and below existing foundations using closely spaced soil nails.

Transportation

Paper No. 5.01 by Zand-Parsa, K. and Zand-Parsa, K. described a simplified method, referred to as KZP5 method, for design of soil nail walls in granular soils. The method assumes linear failure surface and uses trial and error approach to calculate soil nail length with consideration of external sliding and overturning stability factors of safety.

The simplified KZP5 method is an alternative to traditional soil nail wall design methods based on classical slope stability analysis. No case history, however, was presented in this paper.

Paper No. 5.02 by Zand-Parsa, K. and Zand-Parsa K. presented an analysis of a 6.9 m high existing MSE wall subjected to additional surcharge loading from bridge falsework bents located 3.7 m back from the wall face. A method, KZP2, with Boussinesq strip load distribution, was used to estimate lateral wall pressures due to the additional falsework bent loading, and resulted in a minimum factor of safety of 2.86. Wall deflection monitoring during construction indicated practically no movement due to the falsework surcharge.

The case history presented is brief and lacks details. The wall failure mode analyzed is not clear in the paper.

Paper No. 5.04 by Safadoust, J. and Moradi, G. described a 2D plane-strain finite element method (FEM) analysis to investigate the behavior of a 6.1 m high instrumented geogrid reinforced soil retaining wall constructed in Algonquin, Illinois, which was part of a Federal Highway Administration research into MSE walls. The FEM analysis used PLAXIS program and considered two conditions, namely, end of construction and earthquake loading. For the static loading case, the numerical model results were compared to actual field measurements at the end of construction, and showed good agreement with field measured lateral wall deflections, and reinforcement strain and force distributions. The FEM results further indicated high vertical load transfer from backfill to the wall facing panels at end of construction. A 1994 Northridge earthquake time history was used for the subsequent seismic analysis of the wall. The dynamic FEM results indicated that maximum permanent lateral wall deformation near top of wall was four times that at end of construction, and dynamic axial strain in reinforcements could be two to three times that at end of construction. Lateral earth pressures due to earthquake loading were also found to be doubled those at end of construction.

The authors presented the numerical modeling and results in a logical and methodical manner, by calibrating the results of the static analysis with field measurements of the instrumented wall at end of construction, and then comparing results of dynamic analysis with results at end of construction. The dynamic analysis results provide interesting insights into behavior of geogrid reinforced soil segmental retaining wall during earthquake loading.

Paper No. 5.08 by Mojahed, S. and French, M. explained the critical factors leading to the selection of the Soldier Pile-Tremie Concrete (SPTC) Slurry Wall for the Boston's Central Artery/Tunnel (CA/T) Project. The authors described factors such as design attributes, construction considerations, right-of-way, environment, durability and maintenance, cost, and construction tradition that influenced selection of an earth retention system at the CA/T. Due to its stiffness, water tightness, strength and durability, the SPTC was employed on the CA/T project to support excavations, cut off groundwater seepage, serve as final structural walls, and provide underpinning support.

The paper is a review of published information on the selection of the SPTC slurry wall for the CA/T project. No technical wall details or site applications were presented in the paper.

Paper No. 5.10 by Masopust, J. described the reconstruction of pier foundations of the historic Charles Bridge in Prague, Czech Republic. The bridge was built in the 14th century, and has been damaged several times over the past 650 years. The author researched historical records and summarized previous flood damages and repairs to the various bridge piers. The author then described the foundation conditions at Piers 8 and 9, and the subsequent construction of a protective envelope around the existing foundations to protect them against future scour and vessel impact. The constraints included limited headroom beneath the bridge, adverse effects of vibration on the structure, and large boulders in scour holes around the pier foundations that prevented the use of traditional driven sheet piles. The retention solutions adopted consisted of (1) shallow flat steel sheet pile wall supported by jet grout columns reinforced with steel tubes, for sections beneath the bridge, and (2) steel sheet pile wall installed in pre-drilled cement-bentonite slurry filled holes, for sections outside the bridge deck. After the retaining walls were installed, the existing piers were repaired and a concrete collar formed around the pier foundations within the retention systems.

The author described the challenges in repairing this historic bridge, and believed that the flood damage problem at the Charles Bridge is finally resolved with completion of this reconstruction.

Paper No. 5.11 by J. Matos e Silva provided a very brief documentation of the performance of a 13 m high gabion retaining wall located near Lisbon, Portugal. The wall face was monitored with survey monuments at four levels during construction. Maximum horizontal displacements of 46 cm at the top and 9 cm at the base were observed. Some gabion wire baskets apparently broke in the zones of maximum displacements. The author cautioned against the use of large compaction equipment during backfilling adjacent to gabion walls to avoid significant displacements.

The paper is too brief (only 2 pages) and did not provide details of ground conditions and wall construction and backfilling procedures which would help to put the observed wall performance into some perspective.

Paper No. 5.13 by Lien, B., Gómez, J, and Bailey, C. presented the design approaches and construction details of an anchored flexible facing temporary excavation support and accompanying long-term soldier pile wall beneath the south abutment of the Scenic Highway bridge over Interstate Highway I-10 in Pensacola, Florida. Widening of I-10 required cutting back the existing concrete-faced slope pavement below the pile-supported bridge abutment with headroom of approximately 15 feet, and installing a finished vertical wall facing of precast concrete panels. The abutment soils comprised loose to medium dense moist fine sand. The abutment excavation and construction can not disrupt the bridge traffic. A two-phase construction approach was used: a temporary vertical cut supported by mechanical plate anchors and flexible facing that consisted of geotextile fabric and wire mesh; followed by a long-term tieback anchored soldier pile and lagging wall, with precast concrete panel final facing. Flowable fill was placed between the temporary excavation support and the solder pile wall. The finished concrete panel wall gives the appearance of a conventional mechanical stabilized earth wall.

This case history illustrates the successful application of a flexible facing anchored wall for temporary support of poorly graded cohesionless soil, which resulted in significant savings in cost and schedule relative to a conventional soil nailed wall with reinforced shotcrete facing. The authors cautioned, however, that this type of flexible facing should not be used if there is significant seepage or surface runoff.

Paper No. 5.23 by Arsoy, S. described an investigation of a group of failing retaining walls with a total length of 300 m in Kocaeli, Turkey. The reinforced concrete walls were conventional cantilever type, but the higher walls, up to 16 m high, had consoles (horizontal slabs) at mid-height. The walls were founded on competent rock but had displaced excessively by horizontal translation and rotation. The investigation revealed design error in calculation of lateral earth pressures and the use of poor draining backfill that retained water. The remedial solutions used to improve the factors of safety against sliding and overturning comprised base enlargement with clean granular backfill replacement for some walls, and addition of a reinforced shear key to the toe of the wall footing for other walls. Drainage was also improved by covering the backfill with a surface clay layer.

This case history highlights the importance of proper geotechnical design and construction of backfill behind retaining walls.

Paper No. 5.25 by Roth, W., Su, B, Vanbaarsel, J. and Lindquist, E. described an investigation into the cause of strut overloading in two underground stations of Metro Gold Line’s East Los Angeles extension that was excavated in heavily overconsolidated alluvium. The site is located within a compressional geologic/tectonic region with high horizontal in-situ stresses. The excavations were supported by soldier piles and timber lagging with multiple tiers of preloaded steel-pipe struts. Strut loads and shoring deflections were monitored during excavation. Measured strut loads were up to 3 times the design values, resulting in buckling of strut-waler connections. Soil-structure interaction simulation analyses using FLAC program were performed to determine the effects of the high in-situ ground stresses on the excavation and wall performance. The study concluded that the high bracing loads were caused by high in-situ stresses in the region, which had not been accounted for in the shoring design.

This case history illustrates an excellent use of numerical analysis to simulate the excavation and shoring, by matching computed with measured wall performance data, and to evaluate factors that could potentially affect the wall behavior. The authors reiterated that for soil conditions with high in-situ stresses, shoring-design pressures must either account for excess stresses, or the shoring must be allowed to undergo sufficient movement for these stresses to be relieved in a controlled manner.

Paper No. 5.31 by Matta, F. and Nanni, A. described an experimental program on concrete reinforced with glass fiber reinforced polymer (GFRP) bars. The use of GFRP bars, instead of steel bars, in softeyes, which are openings of retaining walls to be penetrated by tunnel boring machines during excavation, is becoming common. The laboratory experimental program, consisting of bending tests on full-scale GFRP reinforced concrete beams, confirmed the validity of the current ACI structural design method for concrete reinforced with fiber reinforced polymer bars.

The paper is intended for structural design engineers. No case history is presented.

Paper No. 5.34 by Kulesza, R, Boussoulas, N and Marr, W.A. discussed the numerical analyses performed for construction of the 26 m deep Halandri Station excavation in hard sandy clays for the Athens Metro extension in Greece. The excavation walls were supported by a row of spaced concrete bored piles, tied back with 7 levels of anchors, and covered with 0.2 m thick shotcrete facing. During design, detailed 2D finite element soil-structure interaction analysis was conducted using the PLAXIS program. Soil input parameters were developed from carefully conducted field and laboratory tests. The excavation supporting system was instrumented and monitored during construction. Comparison of the pre-construction finite element results with measured wall performance data indicated that the measured displacements had similar distribution with depth as those predicted, but were significantly smaller. Subsequently, backanalysis of the anchored soldier pile wall using PLAXIS was performed to match computed to measured inclinometer displacements. The authors concluded that the discrepancy might be due to difficulty in determining properties of hard desiccated soil, lack of information on stiffness anisotropy, and conservatism in soil parameter selection for design.

The authors indicated that the back calculated soil parameters from the Halandri excavation may be useful for design of future excavations in similar soils.

Paper No. 5.36 by Rao, P. J. described the lessons learned from the failure of a reinforced soil retaining (RSR) wall on a major highway in India. A 16 m long section of the RSR wall, with a height of 10.5 m, collapsed 5 years after construction, although it had started experiencing outward movement and rotation during construction. Post-failure investigation concluded that the wall failed progressively over time due to several design and construction deficiencies, namely, (1) unsafe reduction factors used in design to determine strength of geogrid, (2) creep due to high ambient temperature not considered in design, (3) unsuitable fill with high fines content used, and (4) improper geogrid spacing not meeting design used during construction. The failed section was subsequently remediated by buttressing with gabion wall, and other distressed section improved by installing soil nails through the existing fascia panels.

The author has presented a methodical approach to investigate the causes of failure of the reinforced soil retaining wall. The author recommends that future design methods and codes should be based on deformations.

Dams

Paper No. 5.19 by Wang, X., Bernardeau, F.G. and Younan, J.C. described a slurry trench stability analysis to evaluate construction of a cement bentonite (CB) cutoff wall beneath an existing dike in Canadys, South Carolina. The 40 to 55 ft deep CB wall was required to be constructed adjacent (between 0 and 17 ft) to an existing soil-bentonite cutoff wall that had been found to be deficient beneath the crest of a 1.6 mile long ash pond containment dike. The key issue was to determine the safe distance between the CB trench during construction and the existing SB wall. A wedge stability parametric analysis was performed to calculate the factor of safety against CB slurry trench wall collapse due to the influence of the weak SB backfill. The results were presented in a plot of factor of safety vs. distance between walls for different assumed SB backfill friction angles. The stability results provided guidance for construction and for consideration of potential remedial measures in areas where the CB trench was in close proximity to the SB wall. During construction, inclinometers were used to confirm predicted trench stability. The CB wall was completed with an overall overbreak of 1.3 (actual slurry volume to theoretical slurry volume) and only very localized soil collapsing.

The authors have presented a nice case history illustrating the use of the simple wedge method and parametric stability analysis to provide a practical chart to guide slurry trench construction in close proximity to an exiting SB wall.

Paper No. 5.26 by Yan, L., Trapp, D.A. and Sy, A. described the design and construction of a plastic concrete seepage cutoff wall for the new Coquitlam Dam near Vancouver, British Columbia, Canada. The new 30 m high compacted earth core rockfill embankment dam is currently bring constructed at the downstream toe of the existing hydraulic fill dam, which was found to be liquefiable under the design earthquake. As part of the construction of the new dam, a plastic concrete cutoff wall, 0.8 m wide by 150 m long and nominally 20 m deep, was constructed using the slurry panel method of excavation beneath the central core of the new dam. The required strength and stiffness characteristics of the wall were determined during design from 2D static and dynamic finite element stress analyses, and the permeability requirement from finite element seepage analysis. The design criteria were confirmed by a pre-tender plastic concrete trial mix laboratory testing program. Construction of the cutoff wall included contractor's trial laboratory and field programs prior to production, and QA/QC testing during construction that included measurement of in-situ hydraulic conductivity of the constructed plastic concrete panels. The in-situ hydraulic conductivity was determined to be in the order of 10^{-5} cm/s, about two orders of magnitude greater than those from laboratory triaxial cylinder tests.

The authors have provided comprehensive practical details on the panel method of construction of the plastic concrete cutoff wall at Coquitlam Dam. Because of the often conflicting demands on strength and stiffness requirements of plastic concrete mix, they developed a design strength vs. stiffness relationship chart to provide guidance for evaluation of QA/QC test results during construction. They also highlighted the importance of considering in-situ permeability in design, rather than laboratory permeability values of plastic concrete.

Paper No. 5.29 by Gill, R. and Bidasaria, M. described installation of two concrete diaphragm wall cofferdams for construction of the Bisalpur Dam in India. The diaphragm walls were required for dual purposes: to cut off groundwater flow through the 10 to 12 m thick river sand bed, and to divert surface water into the diversion channel. The reinforced concrete diaphragm walls were constructed by the slurry panel method of excavation through alluvial sands and keying 0.6 to 1 m into bedrock. Grouting was conducted to seal joints between panels, and between the wall base and bedrock. The upstream diaphragm wall, less than 12 m deep, had inclined post-tensioned anchors. The downstream wall, up to 28 m deep, was T-shaped, similar to a counterfort retaining wall, and had vertical post-tensioned anchors. The anchors were installed after completion of the diaphragm walls.

This paper described the sequence of construction of the reinforced concrete diaphragm walls at Bisalpur Dam. The walls were successfully installed to reduce seepage to less than 2 m^3/s and allowed construction of the concrete dam in the dry.

Paper No. 5.37 by Sadeghpour, A.H., Ghanbari, A. and Fadaee, M. discussed groundwater control methods in deep excavations, and the foundation excavation for construction of the Shahid Madani dam in northwestern Iran. The groundwater level was 5 m below ground surface, and the site excavation extended 50 m deep through coarse alluvial and colluvial deposits to found the dam core directly on rock. Groundwater controls in the excavation included upstream and downstream cofferdams, clay blanket on upstream cofferdam, deep wells, sumps and drainage channels at base of excavation, and diversion ditches.

The authors emphasized the importance of groundwater control in deep excavations, and the use of several complementary methods to control water.

Miscellaneous

Paper No. 5.03 by Siddarthan and Poraha, A. described a verification study to validate a proposed simplified approach developed by the authors to assess seismic response of deep mixing (DM) treated liquefiable soils. The paper presented an overview of their simplified design procedure to estimate the residual porewater pressure response of DM sites, which allow evaluation of the effectiveness of various configurations of DM treatments. As part of the procedure, the authors developed a database of porewater pressure responses under earthquake excitations based on parametric analyses using the 2D effective stress program TARA-2M. The authors applied their proposed approach to a documented DM treated site representative of the foundation of the 14-storey Oriental Hotel in Japan that was subjected to the 1995 Kobe earthquake. The ground beneath the pile-supported hotel building had been improved by DM. The building suffered negligible damage but extensive liquefaction and ground movements were observed in areas around the building. The simplified approach confirmed the effectiveness of DM treatment in reducing the porewater pressure response (or liquefaction) at locations close to DM treated zone or columns.

The proposed simplified procedure to assess seismic response of DM treated site can provide a practical tool for DM ground improvement design. It is not clear how the 3D DM treatment configuration was accounted for in the authors' 2D numerical modeling. More case history validation and calibration with instrumented DM sites would allow further confirmation of, or improvement to, the proposed simplified method.

Paper No. 5.21 by Evans, J.C. described a laboratory and field study to evaluate the Japanese developed Trench Remixing and Deep Wall Method (TRD) to form vertical passive barrier to prevent salt water intrusion into fresh water at Alamitos Gap in Southern California. The TRD is a one-phase process for excavation and in-situ mixing of soils with added slurry to form a continuous vertical barrier, using specialized equipment. For this study, the slurry composed of sepiolite clay, slag and cement. An extensive laboratory test program, using samples from the site investigation mixed with various slurry blends, was conducted to investigate characteristics of the slurry mixed soils and to determine a design mix. Tests included triaxial permeability and unconfined compression of samples cured in the saline groundwater. The field study consisted of constructing closed test cells with the TRD method, and conducting pump tests and laboratory testing of field mixed samples. The field study showed that for the saline groundwater conditions and the alluvial soils at the site, hydraulic conductivity values less than 1×10^{-7} cm/s and strength greater than 345 kPa were achieved. Long term laboratory tests confirmed the hydraulic conductivity of the mixtures continues to decline with time and that the mixtures were compatible with the saline ground water.

The author has presented a systematic laboratory and field study to evaluate the TRD method for forming continuous in-situ soil mixed walls. The study showed the TRD method can produce walls of low permeability in alluvial ground with saline groundwater conditions and compatibility with site conditions, through the use of sepiolite clay in the slurry.

Paper No. 5.35 by Koudelka, P. presented the results of an experimental test program to examine passive lateral earth pressures against retaining walls, and comparison with values calculated from standard procedures. Unfortunately, the paper is difficult to understand.

FINAL COMMENTS

The 29 case history papers submitted to Session 5 illustrate the great variety of earth retention systems employed in cut or fill construction projects. Most of the systems were successfully constructed and monitored to confirm wall performance after construction.

Six papers (Nos. 5.07, 5.22, 5.23, 5.25, 5.30 and 5.36), however, dealt with investigations into failures of earth retaining structures. These failures involved excessive wall displacements, wall component overloading, or wall collapse. In every failed case presented, design error or deficiency was part of the problems. Designers need to be diligent to ensure that their design calculations and specifications are independently checked and reviewed, that they understand the limitations of the selected earth retaining systems, and that during construction, they have a monitoring role to confirm design compliance.

Eight papers (Nos. 5.04, 5.07, 5.12, 5.17, 5.22, 5.25, 5.33, and 5.34) presented case histories using numerical analyses either to predict retaining wall deformations during design or to backanalyze wall performance. Two-dimensional finite element PLAXIS program and finite difference FLAC program were most commonly used to model the soil-structure interactions of earth retention systems. The engineering profession should move towards deformation-based design, rather than conventional force-based design, particularly for retaining walls in difficult or complex site conditions.

New and hybrid earth retention systems will continue to develop or evolve given the current growth in urban development and in replacement of aging infrastructures. Most of these developments are led by specialty contractors or material manufacturers, and have resulted in significant cost savings. Engineers should keep abreast of these developments and understand the intricacies of new earth retention systems.

REFERENCES

FHWA [1997]. “Geotechnical Engineering Circular No. 2, Earth Retaining Systems”, Federal Highway Administration, Publication No. FHWA-SA-96-038.