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Foundation Movements in Transportation Structures

Prepared for
WHRP Geotechnics
Technical Oversight Committee

Prepared by
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WisDOT Research & Library Unit

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Topic/Problem Statement: Document literature from 2000 to the present relevant to movement of deep and shallow foundation structures (piles and spread footings). Movement may be vertical or horizontal; the new WHRP research project should identify the relationship of movement to pile type and soil conditions.

Keywords: Pile, footing, movement, lateral, deep, shallow, foundation, LPILE.

Summary

We found a considerable amount of research activity on lateral loading and movement in foundation piles and footings, but no current research in progress through transportation agency databases. Of the 19 citations below, six were published in 2005 (including two reports and four journal articles), with three journal articles published in both 2002 and 2006, and two each in 2000 and 2004. We found one journal article published on this topic in 2001, 2003 and 2007.

Citations

Results are listed chronologically, with the most recent citations shown first. Links to online copies of cited literature are provided when available. Contact the WisDOT Library to obtain hard copies of citations.

Title: Modeling Pile Behavior in Large Pile Groups Under Lateral Loading
Author(s): Andrew M. Dodds, Geoffrey R. Martin
Date: April 2007
Source/URL: Report MCEER-07-0004, Multidisciplinary Center for Earthquake Engineering Research, 2007.
Description: 274 pp.
Contents: Large pile groups, defined as pile groups containing a large number of closely spaced vertical piles, were examined using a three-dimensional finite-difference based numerical modeling approach. The specific case of a large pile group subject to only translational loading at the groundline was considered, assuming that a rigid pile cap, whose base is located at the groundline, was present to enforce equal horizontal displacements of all pile heads. Research efforts focused on local pile-soil interaction using p-y curves as the primary assessment tool and p-multipliers to characterize group effects. Analysis efforts were preceded by an extensive review of lateral pile-soil

interaction to provide an assessment of the existing state of knowledge, and a critical review of the three-dimensional modeling approach in terms of its formulation and application to simulating laterally loaded piles and pile groups. Rationalization of a large pile group into a two-pile in-line configuration and a single pile with periodic boundaries was undertaken for the purpose of the research representing typical leading and immediately trailing piles, and internal piles, respectively. Factors considered were: (a) soil type; (b) pile type; (c) initial soil stress states; (d) pile head restraint; and (e) pile spacing. Isolated pile models have provided a benchmark for both the in-line and periodic models. A total of 30 analyses were completed. Overall, the large pile group study indicated that initial stress state, pile type and pile head restraint resulted in some differences, but these were relatively weak compared with the influence of soil behavior and movement. Marked decreases in lateral resistance for interior piles were attributed to the different stiffness and strength characteristics of the soil models, and effects resulting from the boundary conditions employed. Much lower p-multipliers compared with current small pile group recommendations are therefore recommended for large pile groups, implying a comparatively softer translational stiffness for design. While the study enabled greater insight into the mechanics of large pile group lateral stiffness, various issues such as installation effects, pile, pile head and soil conditions remain, ensuring that the task of assessing lateral group stiffness remains a challenging endeavor.

Title: Three-dimensional finite element analyses of passive pile behaviour
Author(s): L.F. Miao, A.T.C. Goh, K.S. Wong, C.I. Teh
Date: June 2006
Source/URL: *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 30 (7), June 2006: 599-613.
Description: 15 pp.
Contents: Piles may be subjected to lateral soil pressures as a result of lateral soil movements from nearby construction-related activities such as embankment construction or excavation operations. Three-dimensional finite element analyses have been carried out to investigate the response of a single pile when subjected to lateral soil movements. The pile and the soil were modelled using 20-node quadrilateral brick elements with reduced integration. For compatibility between the soil-pile interface elements, 27-node quadrilateral brick elements with reduced integration were used to model the soil around the pile adjacent to the soil-pile interface. A Mohr-Coulomb elastic-plastic constitutive model with large-strain mode was assumed for the soil. The analyses indicate that the behaviour of the pile was significantly influenced by the pile flexibility, the magnitude of soil movement, the pile head boundary conditions, the shape of the soil movement profile and the thickness of the moving soil mass. Reasonable agreement is found between some existing published solutions and those developed herein.

Title: Discussion of "Modeling expansive soil movements beneath structures" by Mark J. Masia, Yuri Z. Totoev, and Peter W. Kleeman
Author(s): Brian C. Burman
Date: January 2006
Source/URL: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132 (1), January 2006: 128.
Description: 1 p.
Contents: The discusser feels that the authors of the paper "Modeling Expansive Soil Movements Beneath Structures" needed to include in their model the effect of cracking on ground movement. The authors respond that while the model does not explicitly include ground cracking, the effect is implicitly allowed for.

Title: Behavior of axially loaded pile groups subjected to lateral soil movement
Author(s): W.D. Guo, E.H. Ghee
Date: 2006
Source/URL: *Geotechnical Special Publication No. 153, Foundation Analysis and Design: Innovative Methods, Proceedings of Sessions of GeoShanghai 2006*, 2006: 174-181.
Description: 8 pp.
Contents: Response of a pile due to lateral soil movement and axial load has been investigated extensively by the authors. Typical results deduced from single pile tests in sand are presented previously in terms of effect of pile diameter, soil movement profile, sliding depth and magnitude of axial load. In this paper, a brief description of the apparatus was presented. Results from two model tests were reported, which were conducted on two instrumented pile groups embedded in sand subjected to a uniform lateral soil movement at a sliding depth of 0.57L (L = pile embedment length). Analysis revealed the effect of the direction and depth of soil movement, together with the magnitude of axial load, which are illustrated via profiles of bending moment, shear force, soil reaction, and pile deflection along instrumented piles in groups at various stages.

Title: Innovation Solutions for Slope Stability Reinforcement and Characterization: Vol. III
Author(s): Mark J. Thompson, David J. White, Vernon R. Schaefer
Date: December 2005
Source/URL: IHRB Project TR-489/CTRE Project 03-127, Final Report.
Description: 247 pp.
Contents: Soil slope instability concerning highway infrastructure is an ongoing problem in Iowa, as slope failures endanger public safety and continue to result in costly repair work. Volume I of this current study summarizes research methods and findings, while Volume II provides procedural details for incorporating into practice an infrequently-used testing technique—borehole shear tests. Volume III of this study of field investigation of fifteen slopes in Iowa demonstrates through further experimental testing how lateral forces develop along stabilizing piles to resist slope movements. Results establish the feasibility of an alternative stabilization approach utilizing small-diameter pile elements. Also, a step-by-step procedure that can be used by both state and county transportation agencies to design slope reinforcement using slender piles is documented. Initial evidence of the efficiency and cost-effectiveness of stabilizing nuisance slope failures with grouted micropiles is presented. Employment of the remediation alternative is deemed more appropriate for stabilizing shallow slope failures. Overall, work accomplished in this research study included completing a comprehensive literature review on the state of the knowledge of slope stability and slope stabilization, the preparation and performance of fourteen full-scale pile load tests, the analysis of load test results, and the documentation of a design methodology for implementing the technology into current practices of slope stabilization. Recommendations for further research include monitoring pilot studies of slope reinforcement with grouted micropiles, supplementary experimental studies, and advanced numerical studies.

Title: Response of piles due to lateral slope movement
Author(s): G.R. Martin, C.-Y. Chen
Date: March 2005
Source/URL: *Computers and Structures*, Vol. 83 (8-9), March 2005: 588-598.
Description: 11 pp.
Contents: A displacement method using the FLAC^{3D} program is used to evaluate the response of piles caused by an embankment slope in a translational failure mode, induced by a weak soil layer or a liquefied layer beneath the embankment. The analyses include the kinematic loading acting on the bridge piles caused by lateral soil movements, and the effects of spatial variation of soil displacement on the response of piles and pile groups (2×2). The analysis demonstrates that the proposed displacement method can be applied to design of pile foundations undergoing lateral soil movement or for use in pile-slope stability analysis. Sensitivity studies varying soil and pile parameters are also presented. The results bring out the important effects of relative stiffness between pile and soil on the pile's failure modes. Published case histories are examined and used as a basis for verifying the proposed methodology.

Title: Pile foundation response to lateral ground movement
Author(s): Debanik Chaudhuri
Date: 2005
Source/URL: *Geotechnical Special Publication No. 130-142, Geo-Frontiers 2005*, 2005: 799-813.
Description: 15 pp.
Contents: In some instances, pile foundations are subjected to lateral loading caused by lateral movement of the surrounding soil. This paper describes an analytical method for evaluating pile foundation response to lateral ground movement. A model using beam on linear and nonlinear elastic foundations has been analyzed using the finite difference method. Dimensionless plots are developed to evaluate pile behavior for different soil and geometric conditions. These plots can be used for estimating pile displacements and moments caused by lateral soil movement. Failure mechanisms are examined, and are related to relative soil-pile stiffness and soil yielding. A design example has been presented to demonstrate the use of dimensionless plots and to illustrate failure mechanisms.

Title: Predicted and measured response of precast concrete piles under lateral load
Author(s): J. Kent Hsiao, Sanjeev Kumar
Date: 2005
Source/URL: *Electronic Journal of Geotechnical Engineering*, Vol. 10 G, 2005.
Description: 6 pp.
Contents: Precast concrete piles are often used to support heavy structures. In addition to vertical compressive loads, these piles are subjected to significant lateral loads. Therefore, prediction of lateral load-deflection response of precast concrete piles is of significant interest to structural and geotechnical engineers. Prediction of lateral behavior of pile foundation is complicated due to the fact that the soil reaction is dependent on the pile movement

and the pile movement is dependent on the soil response. Nonlinear behavior of soils and concrete makes the problem even more complicated. Several methods and computer programs are available to analyze the piles under lateral loads. This paper presents the results of predictions made on four, precast reinforced concrete piles which were constructed using coal combustion products. Predictions are compared with the measured data on all four piles. All piles analyzed are 12 × 12 inch square piles. The results presented show that assumption of completely uncracked section or cracked section may not be realistic.

Title: Analysis of vertical loads acting on embankment piles
Author(s): Won-Pyo Hong, Jae-Ho Lee, Kwang-Wu Lee
Date: 2005
Source/URL: *Proceedings of the International Offshore and Polar Engineering Conference*, 2005: 641-646.
Description: 6 pp.
Contents: Embankment piles, the piling method in soft ground under embankments or backfills, can effectively prevent the lateral flow of soft ground by decreasing overburden due to embankments or backfills on soft ground. Theoretical analyses are performed to predict the vertical loads on embankment piles with cap beam and isolated cap, respectively. Failure mechanism such as soil arching failure is investigated according to the failure pattern in embankment on soft ground supported by piles with cap beams. In the investigation of the soil arching failure, the stability in the crown of the arch is compared with the stability above the isolated caps. The factors affecting the load transfer in the embankment fill by soil arching are the space between piles, the width of cap and the soil parameters of the embankment fill. Thus, in order to maximize the effect of embankment load transfer by piles, the factors affecting load transfer in embankment should be appropriately designed.

Title: Lateral load tests on small-diameter piles for slope remediation
Author(s): Mark J. Thompson, David J. White
Date: 2005
Source/URL: *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*, 2005.
http://www.ctre.iastate.edu/pubs/midcon2005/ThompsonLoad.pdf
Description: 13 pp.
Contents: Slope reinforcement and the use of structural pile elements can be an effective slope remediation alternative when conventional remediation practices (e.g., improved drainage) fail to consider the causal factors leading to slope instability (e.g., strength loss due to weathering). An experimental research program was aimed at developing a rapid, cost-effective, and simple remediation system that can be implemented into slope stabilization practices for relatively shallow (< 5 m) slope failure conditions. The non-proprietary remediation technology consists of small-diameter, grouted micropiles. The research program described in this paper establishes the micropiles as a feasible remediation alternative. Details of the experimental testing and the results from selected measurements are presented in the paper. Lateral load tests on drilled and grouted pile elements of two diameters, in which the piles were installed through a shear box and loaded by uniform lateral translation of soil, advanced our understanding of the soil load transfer to the piles. The pile load test plan included three soil types, and the piles were installed into glacial soils of the experimentation site. Instrumentation of the shear boxes and pile reinforcement indicated the load distributions that developed along the piles and the pile response to the physically imposed boundary conditions. Results show that piles installed in failing slopes will arrest or slow the rate of slope movement. Furthermore, the soil movement associated with slope failures induces lateral load distributions along stabilizing piles that vary with soil stiffness and strength, pile stiffness and section capacities, and the spacing of piles over the slope.

Title: Experimental load transfer of piles subject to lateral soil movement
Author(s): M.J. Thompson
Date: November 2004
Source/URL: *2004 Transportation Scholars Conference*, 2004.
Description: n/a
Contents: Remediation of slope failures requires stabilization alternatives that address causes of slope instability. Slope reinforcement and pile stabilization systems, if properly designed, are effective in preventing slope movements in weak soils. Soil load transfer to pile elements from the lateral soil movement as occurs in slope failures is a complex soil-structure interaction problem, and the significant differences in existing design procedures of pile stabilization suggest that the stabilizing mechanisms are not fully understood. The downslope soil movement of slope failures induces unique, unknown lateral load distributions along stabilizing piles. The reliable estimation of these load distributions is important, because the influence of piles on the global stability of the slope depends directly on the pile loading condition. Soil-structure interactions for small-diameter piles subject to lateral soil movement were investigated by conducting full-scale pile load tests, in which piles installed through a shear box

were indirectly loaded by uniform lateral translation of soil. Instrumentation of the shear boxes and pile reinforcement indicated the load distributions that developed along the piles. The load test analyses which succeeded the pile load tests support the claim that the distributed loads which are achieved during pile loading vary linearly with depth. The product of the analysis, which answers a central question of the research, is directly incorporated into the proposed design methodology for soil displacement grouted micropiles. It is apparent from the pile load tests that small-diameter pile elements provide effective passive resistance to lateral soil movement. The proposed, non-proprietary remediation technology, if implemented into current slope remediation practices, offers an alternative that gives consideration to cost constraints, schedule constraints, and constructability concerns of local transportation agencies.

Title: Simulated pile load-movement incorporating anticipated soil set-up
Author(s): M. Hussein, B. Mondello, C. Alvarez
Date: 2004
Source/URL: *ASCE Geotechnical Special Publication No. 126, Proceedings of Geo-Trans 2004*.
Description: 8 pp.
Contents: Dynamic pile testing and related data analysis methods are routinely used to measure soil resistance effects, estimate static pile load bearing capacity, and predict pile load-movement relationship. Analysis results represent conditions at the time of testing. For piles driven into soils with beneficial time-dependent characteristics, the capacity increases with time following the initial driving due to favorable geotechnical effects. In practice, construction scheduling constraints often restrict the evaluation of "long-term" pile capacity and limit the verification testing to a short period following initial driving. This paper presents a method for predicting future pile load-movement relationship based on end of driving and short-term restrike dynamic testing results. A case study is presented where field dynamic tests were performed with a Pile Driving Analyzer (PDA) and CAPWAP computer analysis during initial driving and restrike eleven days later. The CAPWAP method was also used to predict the pile load-movement graph expected at seventeen days after end of initial driving for comparison with results from a full-scale conventional static loading test to be independently performed at that time. Good correlation was obtained between the dynamically predicted and full-scale static load test results based on the proposed method.

Title: Comparative behavior of laterally loaded groups of bored and driven piles in cohesionless soil
Author(s): Michael W. O'Neill, An-Bin Huang
Date: September 2003
Source/URL: *International Journal of Offshore and Polar Engineering*, Vol. 13 (3), September 2003: 161-168.
Description: 8 pp.
Contents: The lateral load performance of 2 pile groups, one consisting of driven displacement piles, the other of bored piles, is described. The effect of installing the piles is to reduce the soil stiffness within the bored pile group, making the soil less efficient in resisting lateral pile movements than in the driven pile group. Structurally, however, the bored piles were more resistant to flexural loading. The net effect was that the system of bored piles was stiffer than the system of driven displacement piles.

Title: Lateral resistance of full-scale pile cap with gravel backfill
Author(s): K.M. Rollins, A. Sparks
Date: September 2002
Source/URL: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 128 (9), September 2002: 711-723.
Description: 13 pp.
Contents: A static lateral load test was performed on a full-scale 33-pile group driven in saturated low-plasticity silts and clays. The steel pipe piles were attached to a concrete pile cap creating a "fixed-head" end constraint. A gravel backfill was compacted in place on the backside of the cap. Lateral resistance, therefore, was provided by pile-soil-pile interaction, as well as base friction and passive pressure on the cap. In this case, passive resistance contributed ~40% of total resistance. The logspiral method provided the best agreement with measured resistance. Estimates of passive pressure computed by the Rankine method greatly underestimated the resistance while the Coulomb method overestimated resistance. Cap movement needed to fully mobilize passive resistance in the gravel backfill was about 6% of the cap height. This is somewhat larger than reported in other studies due likely to the underlying clay layer. P-multipliers developed for the free-head pile group gave reasonable estimates of the pile-soil-pile resistance for the fixed-head pile group once gaps adjacent to the pile were considered.

Title: Three-dimensional analysis of single pile response to lateral soil movements
Author(s): J.L. Pan, A.T.C. Goh, K.S. Wong, A.R. Selby
Date: July 2002
Source/URL: *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 26 (8), July 2002: 747-758.
Description: 12 pp.
Contents: Three-dimensional finite element analysis was carried out to investigate the behaviour of single piles subjected to lateral soil movements and to determine the ultimate soil pressures acting along the pile shaft. The finite element analysis program ABAQUS was used for the analysis and run on a SUN Workstation. The von Mises constitutive model was employed to model the non-linear stress-strain soil behaviour. The pile was assumed to have linear elastic behaviour. This was considered to be a reasonable approximation, as the maximum stress developed in the pile did not exceed the yield stress of the concrete pile. The length of the pile is 15 m, the width of the square pile is 1 m. The three-dimensional finite element mesh used in the analysis was optimized taking into account the computing capacity limitations of the Sun Workstation. The computed ultimate soil pressures agreed well with those from the literature. The shapes of the soil pressure versus soil movement curves and the soil pressure versus the relative soil-pile displacement curves as well as the magnitude of the relative soil-pile displacement to mobilize the ultimate soil pressures were in reasonable agreement with those reported by other researchers.

Title: Ultimate soil pressures for piles subjected to lateral soil movements
Author(s): J.L. Pan, A.T.C. Goh, K.S. Wong, C.I. Teh
Date: June 2002
Source/URL: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 128 (6), June 2002: 530-535.
Description: 6 pp.
Contents: A series of laboratory model tests in soft clay was conducted to investigate the behavior of coupled piles subjected to lateral soil movements ("passive" piles), and to determine the ultimate soil pressure acting on the pile shaft. Two piles in a row (center-to-center "joining" line being perpendicular to the direction of the applied soil movements) and in a line (center-to-center "joining" line being in the direction of the applied soil movements) were considered. The ultimate soil pressures along the pile shaft for two piles in a row and in a line with pile spacings of three and five times the pile width (B=20 mm) were lower than those for single passive piles. Group effects still existed even with a pile spacing of 5 B for coupled piles in a row and in a line. Group factors decrease as pile spacing decreases for piles in a row. The test results also indicated that different distributions of limiting soil pressures along the pile shaft were developed for the single and coupled passive piles.

Title: 3-D elastic analysis of vertical piles subjected to "passive" loadings
Author(s): K.J. Xu, H.G. Poulos
Date: 2001
Source/URL: *Computers and Geotechnics*, Vol. 28 (5), 2001: 349-375.
Description: 27 pp.
Contents: There are many cases where piles are subjected to "passive" loadings by soil movement past the piles. This paper employs a 3-D coupled boundary element approach to analyze the response of vertical piles subjected to passive loadings. A number of theoretical expressions for soil movements are developed and presented. These expressions have been incorporated into the pile-soil governing equation previously developed by the authors. The analysis is employed to examine pile responses when subjected to some typical passive loadings, such as soil shrink/swelling, soil surface surcharge, tunnelling, soil movements arising from driving piles and cavity formation in soil. Reasonable agreement is found between some existing published solutions and those developed herein.

Title: General elastic analysis of piles and pile groups
Author(s): K.J. Xu, H.G. Poulos
Date: December 2000
Source/URL: *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 24 (15), December 2000: 1109-1138.
Description: 30 pp.
Contents: This paper describes the development of a boundary element analysis for the behaviour of single piles and pile groups subjected to general three-dimensional loading and to vertical and lateral ground movements. Each pile is discretized into a series of cylindrical elements, each of which is divided into several subelements. Compatibility of vertical, lateral and rotational movements is imposed in order to obtain the necessary equations for the pile response. Via hierarchical structures, 12 non-zero sub-matrices in a global matrix are derived for the basic influence factors. Solutions are presented for a series of cases involving single piles and pile groups. In each case, the solutions are compared with those from more simplified existing pile analyses such as those developed by

Randolph and by Poulos. It is shown that for direct loading effects (e.g. the settlement of piles due to vertical loading), the simplified analyses work well. However, for "off-line" response (such as the lateral movement due to vertical loading) the differences are greater, and it is believed that the present analysis gives more reliable estimates.

Title: Lateral load capacity and passive resistance of full-scale pile group and cap
Author(s): K.M. Rollins, A.E. Sparks, K.T. Peterson
Date: 2000
Source/URL: *Transportation Research Record No. 1736*, 2000: 24-32.
Description: 9 pp.
Contents: Static and dynamic (statnamic) lateral load tests were performed on a full-scale 3 x 3 pile group driven in saturated low-plasticity silts and clays. The 324-mm outside diameter steel pipe piles were attached to a reinforced concrete pile cap (2.74 m square in plan and 1.21 m high), which created an essentially fixed-head end constraint. A gravel backfill was compacted in place on the back side of the cap. Lateral resistance was therefore provided by pile-soil-pile interaction as well as by base friction and passive pressure on the cap. In this case, passive resistance contributed about 40% of the measured static capacity. The measured resistance was compared with that computed by several techniques. The log-spiral method provided the best agreement with measured resistance. Estimates of passive pressure computed using the Rankine or GROUP p-y curve methods significantly underestimated the resistance, whereas the Coulomb method overestimated resistance. The wall movement required to fully mobilize passive resistance in the dense gravel backfill was approximately 0.06 times the wall height, which is in good agreement with design recommendations. The p-multipliers developed for the free-head pile group provided reasonable estimates of the pile-soil-pile resistance for the fixed-head pile group. Default p-multipliers in the program GROUP led to a 35% overestimate of pile capacity. Overall dynamic resistance was typically 100 to 125% higher than static; however, dynamic passive pressure resistance was over 200% higher than static.