Foundations of Bridges and Other Structures

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The design of foundations and earth retention systems for bridges and highway structures evolved during the 20th century from an early reliance on experience and engineering judgment. As the first half of the 20th century unfolded, the soil mechanics discipline gradually began implementing more rational methods of design and construction quality control (QC). During the second half of the century, the discipline developed at an impressive rate with the advent of more rational and sophisticated analytical design methods, versatile construction methods, robust equipment, and vastly improved methods for nondestructively evaluating the quality of constructed structural elements. The computer revolution, new foundation and retaining systems, and major changes in QC equipment and methodologies dramatically advanced the geotechnical discipline within a remarkably short period of time.

Other major advances in the discipline during the latter part of the 20th century evolved in response to demands and requirements imposed on transportation engineers. Foremost among these are requirements to consider and design for extreme-event load cases, such as seismic events and vessel collisions. Within only about 20 years, these requirements have become one of the key driving forces behind a number of specific advances in geotechnical engineering technology, as well as improvements in the general state of the practice. In the development of the more rigorous designs needed to meet these requirements, the frequency and speed with which new technology and methodologies have been incorporated into mainstream geotechnical practice have been greatly improved. In the new century, the influence of extreme-event design on the state of geotechnical practice not only will continue, but is likely to advance considerably.

In the foreseeable future, the greatest influence on innovation and change in geotechnical engineering is likely to be the implementation and refinement of load and resistance factor design as embodied in the American Association of State Highway and Transportation Officials' (AASHTO's) load and resistance factor design (LRFD) code (*1*). Indeed, a fundamental objective of the new code is to provide the transportation community with a vehicle for implementing innovations and improvements in practice.

AASHTO LRFD DESIGN CODE

The LRFD code was adopted in 1994 by the AASHTO Subcommittee on Bridges. The LRFD code provides clear advantages over the previous design code (*2*) in that the uncertainty and variability associated with design estimates for loads and material resistance are handled separately. In the new century, the code's fundamental objective of achieving more uniform levels of safety in design will provide the impetus for increased monitoring and evaluation of substructure performance and the development of improved design, analysis, and QC equipment and procedures. Use of more rigorous and sophisticated methodologies with greater reliability will be rewarded by higher and potentially more cost-advantageous design resistance factors.

When the new code was adopted, considerable preparation had been made for changing design procedures in the superstructure area, but a similar level of effort had not been devoted to the geotechnical aspects of bridge design. Hence implementation of the geotechnical sections of the LRFD code has lagged somewhat behind that of the superstructure design provisions. Other obstacles to implementation of the new code include the limited experience engineers have with LRFD-based geotechnical methods and codes in the United States. Extensive training, therefore, will be required to implement the code fully and effectively. Hence full utilization of the code will be realized only if significant effort and resources are applied during the first decade of the 21st century.

At the end of the 20th century, there was widespread recognition of the need for diligent efforts to address these barriers to use of the LRFD code. Significant resources have been expended during the latter 1990s on resolving LRFD geotechnical design issues, and on developing training courses and manuals to improve the effectiveness of the code's implementation. It is commonly recognized that such efforts will need to be sustained or increased in the early years of the next century.

The most prominent area of LRFD research and development in the coming decades will be the formation and maintenance of large geotechnical databases defining the geotechnical and structural performance of foundations and earth retention systems. The basic structure of the LRFD code makes these databases fundamental to the formulation of the reliability-based load and resistance factors needed for both existing and new geotechnologies.

The general consensus among many geotechnical engineers is that new developments in the foundation area will be gradual. New equipment and methods will continue to appear. However, radical changes will be less likely than has been the case during the last 30 years, a period that saw tremendous advances in the areas of both driven and cast-in-place deep foundation systems. This rapid change in deep foundation geotechnology has been accompanied by the development and application of a variety of electronic instrumentation and digital computer devices for improved QC. With implementation of the LRFD code and its structure for rewarding greater reliability, it is anticipated that innovation in geotechnical QC technology will be dramatic and rapid in the early years of the new century.

SPREAD FOOTINGS

There have been no substantial changes in spread footing construction recently, nor are such changes expected early in the 21st century. It is important to note, however, that this lack of change does not reflect poor performance on the part of the geotechnical community, but the fundamental advantages of spread footings—their simplicity and low cost.

A primary limitation on wider usage and acceptance of spread footings has been the perception of designers that highway structures cannot tolerate more than small vertical and lateral displacements. In fact, research sponsored by the Federal Highway Administration (FHWA) during the 1980s (*3*) demonstrated that spread-footing foundations supporting simple- and continuous-span bridges can tolerate substantially larger deformations than are usually considered acceptable. Therefore, until tolerable displacement limits are increased, the application of spread-footing foundations will likely remain limited for highway bridges.

The changes foreseen for spread-footing design and construction will most commonly result from the implementation and evolution of the AASHTO LRFD code. In recognition of the importance of displacement in controlling the design of spread-footing foundations, future changes to the new code will reflect a reliability-based consideration of foundation performance under service load conditions, which will likely result in more economical designs and more frequent use of spread footings.

While overall design and construction methodologies for spread footings are not expected to change substantially in the foreseeable future, the use of spread footings for bridges is expected to increase gradually in the new century where foundation soil scour is not a design consideration. This increased usage will be encouraged by the fundamental economic advantage of spread footings as compared with deep foundations, in combination with the expected impact of the LRFD code on spread-footing design efficiency.

DRIVEN PILES

Driven piles have long been the deep foundation of choice among bridge designers. However, changes in design codes and construction requirements during the last decade have reduced the dominance of driven-pile foundations for bridges. Primary among the reasons for this shift has been AASHTO's adoption of design code requirements for foundation scour and extreme events, such as vessel collisions and earthquakes.

While scour events have resulted in the virtual elimination of spread footings for water crossings in favor of driven piles, hydrologic and hydraulic studies have frequently produced design requirements for pile penetration that are not achievable (e.g., deep penetration of rock). In addition to, and sometimes in combination with, scour requirements, extreme events often pose acute lateral loading conditions that can make a driven-pile alternative unmanageable in size; very time-consuming to construct; and uncompetitive with other foundation systems, such as drilled shafts, which possess greater bending stiffness and can be socketed into rock.

As was the case for much of foundation engineering during the 20th century, changes in driven-pile technology were gradual until the last 30 to 40 years, when rapid developments in driving hammers and QC occurred. Recent developments in pile-driving hammers have followed two main paths: (1) hammers that produce greater energy, usually through larger strokes and higher impact velocities; and (2) improved methods for estimating pile driveability and resistance.

A trend toward increased pile design capacities that has been under way for the past three decades will probably accelerate in the near future. Hammer performance has become more reliable with the advent of hydraulic hammers incorporating impact velocity measurement devices. This trend will continue with other hammer types. Improved hammer performance and reliability, coupled with higher impact velocities, will enable further increases in pile capacity due to both harder driving and the use of smaller safety margins. To accommodate the harder-driving requirements, higher-strength pile materials will be necessary. Steel piles yielding strengths of 50 kips per square inch (ksi) and higher are readily available, and concrete pile strengths of up to 12 ksi are possible with little cost penalty. The skill and experience needed to drive these higher-strength materials must be developed, along with an attendant increase in the in-service stress limits imposed by design codes and employed by designers.

During the latter part of the 20th century, major technical strides were made in the prediction of pile driveability and resistance. These advances included computational methodologies for the prediction of driving resistance and static capacity, computer analysis and design tools, and electronic instrumentation and digital computer QC devices. Because of the unique relationship between design code requirements and construction QC (safety margin and resistance parameters used for design are based on the QC methodology employed), these advances have had a profound impact on the overall design and construction process for driven piles with regard to both productivity and quality. Improvements in construction QC have led to commensurate improvements in design codes, which have resulted in turn in the development of better QC methodologies.

The immediate future will see improved QC equipment and procedures employed at lower cost. Developments in electronics and communications will reduce the cost of dynamic testing, perhaps dramatically. Implementation and refinement of the new LRFD code will strengthen and expand the unique relationship between design codes and QC. Further enhancement of the codes and QC equipment will be accomplished through the increased use of static and dynamic axial and lateral load testing. Additional advances in driven-pile design and QC practices will require a much improved understanding of, and experience with, soil dynamics. Such advances will be essential for more rational foundation designs for extreme-event loading conditions and for improvement of pile-driving QC equipment and methodologies.

DRILLED SHAFTS

Although driven piles have long been the deep foundation of choice for bridge design, advances in cast-in-place foundation technology, changes in design codes, and constructability requirements have made drilled shafts a common alternative during the past 20 years. As with driven piles, one of the major factors behind this change has been increased concern about scour problems in the design of bridge foundations for water crossings and about large lateral loadings from extreme events, such as vessel collisions and earthquakes. Other recent influences on the selection of a drilled-shaft foundation as the preferred option include the need for a small foundation footprint because of limited space or the need to maintain traffic flow, noise restrictions, and vibration and settlement restrictions associated with nearby bridges and buildings.

In the near future, application of the new AASHTO LRFD code should have a large impact on the design, construction, and acceptance of drilled shafts. The new code's inclusion of construction methods, construction QC, and performance testing should serve as a catalyst for improvements in drilled-shaft technology. In addition, as the technology and the LRFD code evolve, instrumentation and methods for qualifying and quantifying the integrity of drilled shafts will become more economical and commonplace. Axial and lateral load testing of drilled shafts will also increase as the economic benefits of load testing become more apparent. The use of dynamic capacity testing will be increasingly common in the next century, not only because of the speed and potential cost savings associated with these methods, but also because of new dynamic design methods and tools that will require dynamic soil input parameters.

A summary of the application of earth-retaining systems up to 1990 (*4*) categorizes earth-retention structures as either externally stabilized (gravity or in situ walls, such as soldier pile, sheet pile, and internally braced) or internally stabilized [reinforced soil walls, such as mechanically stabilized earth (MSE) or soil nailing, or in situ reinforcement walls, such as soil nailed]. Since that time, development efforts have focused primarily on internally stabilized systems with regard to the development and application of new design methods by geosynthetic reinforcement systems, modular block facing systems, and connections used for MSE structures. During the next 10 years, advances in these and other areas will likely continue and should result in improved performance and reduced unit costs. These advances could include the following:

- Improved application of deep-soil mixing and jet grouting for construction of in situ gravity walls;
- Construction of anchored walls using single-bore multiple-position anchors to increase load capacity;
- Development of high-strength, nonmetallic, corrosion-resistant materials for construction of anchored and nailed walls;
- Improved geosynthetic reinforcement with greater resistance to the effects of long-term degradation and construction damage;
- New dry-cast modular block facing systems with improved durability for MSE applications;
- Stronger and more durable connections between block facings and geosynthetic reinforcements;
- Use of lightweight backfill to reduce earth pressure;
- Application of fiber-reinforced, pneumatically applied concrete for facing of soil nailed walls;
- Use of pneumatically applied, polymer-impregnated soils to face cut slopes in soil; and
- Application of limit state design (i.e., LRFD) methods for walls.

To facilitate implementation of these advances for highway applications, objective system evaluations, such as the Highway Innovative Technology Evaluation Center (HITEC) Earth Retaining System Program (*5*), will be needed. Such evaluations will help ensure designers and owners that these products meet accepted standards for material, design, construction, and performance.

At the beginning of the 21st century, advances in seismic design methodology will likely include the continued evolution of criteria for design ground motion needed for performance-based design. Current AASHTO guide specifications call for design on the basis of ground motions with a 10 percent probability of not being exceeded in 50 years. In 1997 the FHWA/Multidisciplinary Center for Earthquake Engineering Research (MCEER) Workshop on National Representation of Seismic Ground Motion for New and Existing Highway Facilities generated the recommendation that design ground motions be increased to a level corresponding to two-thirds of the ground motions with a 2 percent probability of not being exceeded in 50 years (*6*). This change probably represents just an interim step in the evolution of design ground motions. Design ground motions for tall buildings recommended by the Structural Engineers Association of California and the Building Seismic Safety Council reflect a shift toward the concept of performance-based design. In performance-based design, the designer considers a menu of multilevel performance objectives, with each level of objectives linked to a specified probabilistic design ground motion level.

Ground motions with a 2 percent probability of not being exceeded in 50 years are generally used as the design criterion for the most stringent performance objective. For ordinary structures, this most stringent performance objective is generally based on safety considerations. For critical structures, such as lifelines, achieving this objective may require maintaining serviceability or limiting potential design damage to that which can be repaired rapidly. Performance objectives for less extreme ground motion levels may include repairable damage and, for the highest-probability ground motion level (e.g., for a ground motion with a 50 percent probability of not being exceeded in 50 years), no damage.

Application of performance-based design will drive the development of more sophisticated methods of analysis capable of predicting seismic performance at a level consistent with these performance objectives. These methods will likely include nonlinear time domain analyses of foundation response to seismic loading for piles, pile groups, and shallow foundations to account properly for soil-structure interaction effects.

CONCLUSION

From a historical perspective, the design of earth-retention systems and bridge foundations began during the 20th century in much the same manner as most technology at the time, demonstrating gradual and consistent levels of improvement. As the century progressed, the rate of change increased in all technological fields, including geotechnology. Advances in mechanics, electronics, and computational tools changed the way society in general, and geotechnology in particular, works and thinks. In many ways, these advances have placed a much larger burden on geotechnical engineers. New awareness and demands associated with urbanization, environmental impact, natural hazard mitigation, economic efficiency, and sustainable development present major and pressing challenges for geotechnical engineering in the coming century. As the Latin root of the word “engineer” implies, ingenuity is the key.

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