A2K04: Committee on Subsurface Soil-Structure Interaction
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Soil-Structure Interaction of Buried Structures

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The analysis, design, and performance of buried structures associated with transportation facilities, such as buried culverts, grade crossings, and soil-structure systems, requires an understanding of soil-structure interaction. Buried structures usually cannot resist the loads to which they are subjected, including soil, without utilizing the strength of the surrounding soil in a complex interaction. The soil-structure interaction of a buried structure is affected by the structure's material, size, and stiffness; by the method of construction in the field (e.g., trench, embankment, or tunnel); by the type and placement of the backfill material; and by the external loading.

TRENDS AFFECTING SUBSURFACE SOIL-STRUCTURE INTERACTION

During the past few years, a number of trends have led to changes in the designs for buried structures. In the coming decade, the following trends are expected to result in further changes to buried structures:

- Rehabilitation of existing structures will become a more important aspect of work associated with buried structures.
- New or improved materials will continue to be developed for structures and for backfill.
- The weight of vehicles on highways will increase.
- Environmental restraints and limitations on public disruption will continue to affect construction.
- Some resources, such as high-quality fill, will become less available and thus more costly in some locations.
- Computational power will increase, and new computers will cost less than the computers of today.
- Reliability-based design will emerge as the use of load and resistance factor design (LRFD) increases.
- Property-monitoring equipment will improve in cost and ease of use.
- Research into problems and unknowns associated with soil-structure interaction will result in improved performance prediction and more reliable designs.
- Competitive forces will lead to streamlining of design, construction, and quality control processes through the development of innovations in subsurface structures.

Structural Materials

The materials used in buried structures are principally metals, concrete, and plastics. Each type of material has unique properties and responds differently to the surrounding soil. As a result, material-specific design criteria have been developed. Many factors are involved in the choice of the structural material to be used. These factors include strength, toughness, stiffness, corrosion resistance, weight, compatibility with foundation movements, required quality control during construction, method of installation, and local availability.

Concrete grade crossings and culverts are termed rigid, since their stiffness results in little deformation under loading. This stiffness, combined with the nature of the bedding, can result in increased earth loads above overburden pressure. As a result, soil loadings for rigid structures are formulated differently from those for flexible structures, and compressible inclusions in the fill or bedding are considered in the design. Concrete can be relatively corrosion resistant and stiff, and require less compaction control of backfill. For cast-in-place and wet-cast concrete structures, epoxy-coated rebar has been used to slow rebar corrosion. Fiber-reinforced plastic rebar is also being investigated to reduce rebar deterioration. Cast-in-place concrete structures can be designed for almost any shape and size. However, precast concrete structures with spans of up to more than 10 m are now becoming more common among larger concrete structures.

Metal grade crossings and culverts, including corrugated, galvanized steel and corrugated aluminum, are considered to be flexible structures, although steel and cast iron pressure pipes are rigid as compared with the soil stiffness. Flexible structures interact extensively with the surrounding soil, and the soil becomes part of the resistance to the load. The soil loads for flexible structures can exhibit arching, which reduces the soil load to below the overburden load. For large-diameter flexible structures having spans of up to more than 15 m, the quality and properties of the backfill are important to the proper performance of the structure. Concrete relieving slabs have also been used to spread live loads over larger areas. Since the long-span structures are flexible, compaction forces must be controlled to reduce deformations of the structure during compaction. Aluminum has better corrosion resistance than steel for a number of services, including coastal marine service, but has lower strength.

In the past two decades, pipes made from polyethylene, polyvinylchloride, and other plastics have captured an increasing share of the total market for buried structures. While plastic pipes have been limited in size, new wall profiles have pushed current diameters to 2 m, and diameter limits are expected to increase. Plastic pipes are flexible, and thus involve many of the considerations noted above for flexible metal structures, and some of their properties are time dependent. More field performance testing is needed to determine the effects of the time-dependent properties of plastic. Plastic is lightweight, which results in ease of handling in the field; it is also resistant to many forms of corrosion.

For rehabilitation, it is not uncommon to have a composite structure (e.g., an existing metal shell, a new plastic liner, and a cement grout filler between two pipes). However, design criteria and analytical techniques have been developed for new installations, and thus do not apply directly to these composite structures, which are likely to be neither flexible nor rigid. Rehabilitation criteria and design procedures for structures of intermediate stiffness will be needed in the future, as will more performance measurements.

Fiber-reinforced plastic is being developed for many uses in the transportation field and has begun being used for buried structures. Carbon or glass fibers can be designed to provide custom properties. More widespread use of this material may occur, and design procedures for reinforced plastic will continue to be developed.

Special Features

A number of special features are used for buried structures, all of which have an effect on soil-structure interaction. Longitudinal stiffeners on flexible long spans promote compaction and live-load stress distribution in the longitudinal direction. Transverse stiffeners on the top portion of the buried structure resist peaking deformations from compaction and live loads. Relieving concrete slabs placed in the soil above the crown of buried structures reinforce the soil above the crown and also distribute live loads over a wider area. Soft inclusions of expanded polystyrene and other materials are used above or below rigid structures to reduce excess soil stresses caused by arching onto the structure. It is expected that the new millennium will see continued development of innovative special features for buried structures.

Placement of Buried Structures

Buried structures are placed with three basic methods: trench excavation, embankment filling, and tunneling. Each method affects the soil-structure interaction of the buried structure in a unique way, and special design provisions have therefore been developed for each.

Trenches are often excavated in existing roads, and their use is especially common in cities for placing utility pipes. With the trench method, backfill soil loads are typically less than the overburden, since shear from the walls of trenches will partially support the soil column over the buried structure. The additional lateral load from arching of the overburden has not yet been fully utilized in the design of buried structures.

For construction of new embankments, the fill is placed in wide layers and built up around the structure. Construction in this manner deforms flexible structures. Construction control, including filling sequence and compactor size, is important during the filling process to restrict asymmetrical or excessive deformations. Even with light compactors, accumulated inward movement can cause peaking of flexible culverts. If the structure is stiff, the vertical loads on the culvert for embankment construction can exceed the overburden, since soil side shear adds more forces onto the overburden soil over the culvert.

As the technical capability to jack and bore for buried structures develops, tunneling methods are being more widely used. These methods are being encouraged because of concerns for protecting the environment, as well as for reducing disruption to the public. Tunneling methods are used to install pipelines with little or no surface distress. Soil loads can also be significantly different from trench installations. After a certain depth, the soil loads on a tunnel often are not significantly affected by cover height.

Surrounding Soil

The surrounding soil, or soil envelope, is an integral part of the strength of a pipe. Thus the design is aided by the use of high-strength, well-compacted soils around the structure. For most installations, this surrounding soil is controlled backfill comprising primarily selected soils. Under some circumstances, flowable fills are used to replace the selected soils. For jacked or bored installations, natural soil surrounds the structure.

Soils for backfill are restricted to A-1, A-2, and A-3 classifications and must be compacted to a density of more than 90 percent of Standard Proctor maximum dry density to maintain high strength. Thus proper specifications and monitoring of soil classification and compaction level in the field are important for the performance of the structure. As improved instruments make testing for properties more convenient, it is expected that more property testing will be done to improve performance predictions.

The extent of backfill is prescribed to permit space for light compaction equipment. Movements in the natural soils of foundations are considered in the design, but this is generally not the case for movement of the natural soil beyond the backfill envelope.

Controlled low-strength material, or flowable fill, is a cement-soil-flyash mixture placed without compaction. This material is designed to be weak enough to excavate, but at least as strong as compacted high-quality soil. It is more costly than soil backfill, but is especially useful in tight situations, e.g., where many utility lines cross an excavation. The material has been used in a number of installations of buried structures, but is expected to have wider application in the future.

In cold climates, frost will penetrate the walls of an at-grade crossing or a culvert. Some A-2-4 and A-2-5 materials currently allowed for backfill around buried structures are susceptible to frost. Frost lens buildup in these materials can deform the structure wall, while the melting of these lenses in the spring can cause loss of the lateral support necessary for the structure’s proper performance. The possible effects of cold temperatures on frost-susceptible structural backfill require further investigation.

Bored and jacked subsurface structures will be surrounded by natural soils with a much greater range of properties than is the case for selected compacted backfills. Thus the behavior of soil around a buried structure placed by tunneling techniques is expected to be different from that of soil placed in an embankment or a trench. If sufficient depth is obtained, loads should more closely approximate those on tunnels, instead of those on structures placed from the surface.

Live Loadings

Live traffic loadings become more significant at lower cover. Wheel pressures for design are assumed to be average pressures, calculated as though soil were a homogeneous, elastic material. This approach neglects the presence of the pipe, which has different properties in the transverse and longitudinal directions. In flexible pipe design, this pressure is assumed to be applied over the entire span of the structure, an assumption that becomes increasingly conservative as spans increase beyond the significant zone of distributed pressure. However, bending effects are not accounted for in design. Rather, minimum covers are developed through experience.

When the live load is a small percentage of the total load on a structure, as happens with relatively deep structures, limitations in the prediction model are not very important for design. However, for shallow cover and for the expected higher loads of the future, it is important to improve the predictive capabilities of the live load by including the significant variables in the prediction process.

Soil Characterization

Soil is characterized in design equations for buried structures by its unit weight, modulus of elasticity, coefficient of lateral earth pressure, and friction angle. The unit weight of the material can be measured reliably in the field, but modulus of elasticity, coefficient of lateral earth pressure, and friction angle that are developed in service can vary considerably since they reflect soil strength. Strength development in soils depends on strain mobilization as well as other factors, and strain development varies considerably from place to place around a buried structure. To predict performance in soil-structure interaction, it is necessary to have realistic constitutive relations—that is, relations for stress and strain—for soil materials, as well as for the structure.

For buried structures, buckling criteria for flexible structures and distribution of live load with depth are based on the assumption that the soil behaves as a linear elastic material. Under the conditions in which buckling and distribution of live load are important—at shallow cover and under heavy loads—soil resistance is quite nonlinear to strain and likely has local yielding. Thus the buckling criteria and distribution of live load must be reexamined as further development of structures occurs.

In the design methods, not only are linear elastic conditions assumed, but also complete yielding (plastic condition) of the soil. For ring compression of flexible structures to be valid, there must be soil stress redistribution around the structure that assumes yielding of the soil. Yielding may occur under some conditions, but for certain flexible structures, such as arches, the assumed yielding may not take place near the footings. For rigid structures, the arching loads reflect the assumption that yielding has occurred in the soil, but under some conditions, full yielding may not have taken place.

The soil may behave linearly elastically at a distance from the structure and behave plastically near the structure. To make deformation or stress predictions for checking in the field, a realistic soil model should be used, rather than a design model using conservative values. The hyperbolic model used in finite-element models for soil-structure interaction reflects many of the variables that occur in soil behavior, such as stress-dependent moduli. Improvements beyond the hyperbolic model are expected to occur as soil strength characterization is refined as a result of increased computing power.

Load and Resistance Factor Design

With the newly introduced LRFD for soil-structure interaction, the application of factors to both varying loads and resistances should reflect a more rational approach to safety and a more repeatable reliability in design. One of the difficulties in using LRFD for the soil-structure interaction of a buried structure is that the unit weight of soil is a load in one location and acts as part of the frictional resistance in another location. Thus if all unit weight in a soil-structure interaction is given a load factor, resistance is increased in some locations, instead of being reduced. This difficulty with the use of LRFD in soil-structure interaction design, including the use of finite-element programs, will have to be resolved if repeatable reliability in design is to be obtained.

Design Methods

For a given structure, there may be multiple collapse mechanisms or ultimate strength limit states. Ensuring that all relevant strength limit states are addressed is usually more important for safety than is variability in parameters. For each strength limit state, deformations, or service limit states, are often not calculated under service conditions, but presumed to be within acceptable values if the strength limit value is not exceeded for factored conditions.

For metal and plastic flexible structures, three strength limit states—thrust failure, buckling, and flexibility—plus seam failure for metal pipe with seams, are concerns for the structure. Flexure is considered for metal box culverts. For long-span metal structures, for which flexure and buckling should be most worrisome, only thrust failure and seam failure limit states are checked. For structures supported by foundations, the strength limit state of bearing capacity must be addressed. Service limit states (i.e., deformations) under service conditions are specified for foundation conditions for the structure and footings, but not for the structure itself. For concrete structures, four strength limit states are checked: thrust, flexure, shear, and radial tension. For service limit state, crack width is checked.

Prescriptions (i.e., codifications of good practice) may be as important to a reliable design for buried structures as formulation of the strength or service limit states. Whenever design methods are changed, it is important to recognize the value of these prescriptions, such as those pertaining to construction, special details, and material quality, to the quality of the design.

The design can also be developed using finite-element computer programs. These programs not only contain more realistic soil constitutive models than the design equations, but also can model the effects of items such as incremental construction and special features. Programs that have been used in practice include CANDE (*1*) for flexible and rigid structures and SPIDA (*2*) for rigid structures; however, these programs lack three-dimensional analysis capabilities. For new programs, it is important to calibrate them to existing practice.

CONCLUSIONS

Soil-structure interaction for buried structures will evolve as a result of innovations developed through research and competition, aging infrastructure, depletion of resources, and further mandates regarding safety and environmental protection. However, successful performance of a buried structure will still depend on the structural product used, construction in the field, monitoring of behavior during construction, and analytical techniques. All of these elements are interrelated, and this interrelationship must be recognized if the cost and safety aspects of buried structures are to be maintained or improved.

REFERENCES

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