The Safety Factor in Excavations and Foundations

GEORGE F. SOWERS, Senior Vice President, Law Engineering Testing Company, Atlanta, and Regents Professor of Civil Engineering, Georgia Institute of Technology

•A SECONDARY road in a midwestern state was constructed on an embankment across a small ravine. The design of the embankment followed the usual standards of the highway department in providing a reasonable margin of safety against shear failure. The pavement also was constructed in accordance with the usual standards with a substantial margin of safety against failure under the traffic loads. A culvert was installed beneath the embankment to dispose of the runoff that accumulated in the ravine upstream from the embankment. Its design, too, incorporated a reasonable factor of safety.

After several years of satisfactory performance with no indications of distress, the embankment suddenly failed (Fig. 1). The failure was the result of a chain of circumstances. Debris, from cutting undergrowth nearby, was eroded from the steep slopes of the ravine, and it accumulated at the culvert entrance. The embankment with its clogged culvert became a dam with water ponded behind it. The soil in the embankment became saturated, a condition that was never anticipated in the original design. The continuing saturation and seepage through the embankment weakened the soil enough so that a shear failure developed on the downhill side. More than half of the road was taken by this failure.

This illustrates the complex nature of the problem of the margin of safety with respect to failure. The original design included adequate safety factors for the conditions anticipated in these highway embankments. It is obvious that there was not a sufficient margin of safety with respect to possible but unusual conditions. A peculiar chain of circumstances, unforeseen by the design, produced a rather ordinary type of shear failure.

The problem of safety in engineering and construction is becoming increasingly important. The traditional views of safety as well as the design provisions for providing safety are undergoing change for a number of reasons:

1. Designs are becoming increasingly daring, departing from the ordinary or from past experience. Excavations are deeper and structures are heavier. Moreover, these cause much more drastic changes in the environment.
2. The structures are becoming more critical—less tolerant to movement. Modern frame structures develop severe secondary stresses as a result of differential movements of the foundations; the complex structures erected today are much more sensitive to tilting and misalignment than the simple structures designed and constructed 50 years ago.
3. Sites for construction are becoming progressively poorer. In populated areas the best construction sites are already occupied by structures. Only the marginal land usually passed over because of unfavorable site conditions is available. Geometric design dictated by safety and speed dominates highway location, and considerations of foundation and material quality have become secondary.

In addition to the engineering problems involving safety, there are important legal and economic considerations that dictate a new look at safety requirements. First, the

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Figure 1. Slide of a highway embankment weakened by saturation caused by a clogged culvert.

economic squeeze imposed by increased design and construction costs has made it necessary to shave the safety factors to the barest minimum. At the same time, the lack of planning money has sometimes made it impossible to undertake the thorough investigation of site conditions that must accompany a reduction in the margin for safety.

Similarly, the squeeze of time has added its effect. The public demands better highways and better structures immediately; the urgency generated by public opinion frequently does not permit enough time for the necessary thorough evaluation of site conditions before construction begins.

Unfortunately, the demand for cheaper structures built in less time has been accompanied by increasing intolerance of risk by society. The public has become exceedingly claim-conscious, probably lured on by the exorbitant damage awards sometimes made by ill-advised juries in accident cases. In a recent magazine article a prominent attorney, a leader in the Association of American Trial Lawyers (the association of attorneys whose fees are generally a third to a half of the damages awarded in cases of failure), has stated that our society demands that engineers be morally and economically responsible for failures. He implies that this is a shift in the position that has governed American society since the building of this nation. The original American philosophy was that progress inherently requires risks and the damages resulting from this risk are the price that society as a whole must pay. With this traditional position the author agrees.

However, the attorney maintains that now the need for such progress at the cost of risk has ended. Society, elevated to a plateau of affluence, no longer requires a rate of progress that demands risk. It is the author's opinion that this attorney is seriously misinformed regarding the expanding needs of the world. Risk is inherent in life but particularly inherent in progress. This growing tendency on the part of certain members of the legal profession to demand payment by somebody for the risks of existence and progress (and legal fees in proportion) is a threat to the very progress that has transformed the life of this nation during the last half-century. The growing application of this concept can only result in a lack of progress and a stagnation of engineering initiative. However, the growing unwillingness of society to accept risks in obtaining progress now makes it imperative that the engineering profession reevaluate the philosophy of safety in design and construction.

SAFETY FACTOR

The safety factor is difficult to define accurately. In its fullest sense, it is the margin of resistance of the structure to failure. In a more restricted sense, it is the ratio of the resistance to failure to the unbalanced force that might cause failure. For a small, simple component of a structure like a beam, the safety factor can be defined accurately with ease. However, the evaluation of that safety factor is seldom precise because neither the resistance to failure nor the unbalanced forces causing failure can be determined accurately in advance.

The overall safety factor of the structure is more difficult to define because it depends on the interaction of all of the components of the structure. The individual components all may be adequately safe. When these components are joined together, however, certain secondary stresses that were considered in the evaluation of the individual components may govern the overall safety.

The complex nature of the safety factor can only be understood by considering all the technical components that are involved. Essentially, it is a technical measure of the unknown or, in less elegant terms, of the ignorance of the designer. The most important of the components that influence the safety factor are listed in Table 1. The site conditions are among the most difficult components to evaluate quantitatively because of the extremely complex nature of the soils, rock, and groundwater conditions. Moreover, these site conditions are dynamic, changing with the seasons, and even changing as a result of the new construction. The saturation of the embankment in Figure 1 is an example of an environmental change that led to failure.

The material properties of the site and the engineering structure are equally difficult to evaluate. Moreover, the site properties are dynamic, as was previously mentioned. The science of evaluating these properties has not progressed to the point that all of the future behavior of soil and rock can be predicted, even when the environmental changes are known. To a lesser degree, the dynamic changes apply to the materials of the engineering structure. Their properties are altered by temperature and with repeated loading. The recent collapse of a bridge over the Ohio River, years after it was placed in service, apparently was a result of fatigue, a dynamic change in the structural behavior of the material.

The magnitude of the load to which the structure will be subjected is difficult to evaluate. The dead load can be predicted accurately. The designer selects design live loads based on codes, laws, and experience. The capacity to resist these loads becomes an inherent property of the structure. However, the ignorance of the owner or the bowing of a legislative body to lobbying or political pressure can upset the engineer's design by arbitrarily permitting live loads greater than those that were anticipated. For example, state legislatures have increased the loads permitted on highway vehicles as blithely as if the change in the load law could cause a change in the strength of all of the components of the highway. (While we must agree that the politicians have many occult powers, it has not yet been demonstrated that they have the magic wand for increasing soil and rock strengths.)

Sometimes even engineers are misled into permitting load increases because there has been no sign of distress with the original design load. Such progressive failures as the fatigue of the Ohio River bridge are not likely to develop at low levels of stress, but beyond a threshold level of stress, creep, and fatigue, failures become increasingly important. Therefore, stresses cannot be increased just because a long life has indicated that the original design might have been conservative.

TABLE 1

THE ELUSORY OR ILLUSORY FACTOR OF SAFETY AND ITS COMPONENTS

I. Sources of ignorance involved in design
  A. Site conditions
  B. Material properties
  C. Loads on structure
  D. Inaccuracies in analysis
  E. Changes produced by construction
  F. Changes produced by structure
  G. Changes of environment

II. Consequences of failure
  A. Direct costs
    1. Cost to owner
    2. Cost to neighbors
    3. Cost to users
  B. Liability of owners, designers, constructors

III. Failures not related to the safety factor
  A. Complementary structure: natural and man-made
  B. Excessive deflection producing failure

IV. Safe because of failure
  A. Shear mobilization
  B. Safety valve
  C. Warning

A major component of the margin for safety, therefore, lies in the margin of uncertainty of the future loads: their magnitude, duration, and frequency. The total view of the problem is given in Table 1.

THE SOIL-STRUCTURE SYSTEM AND FAILURE

The resistance against failure is provided by an assemblage or system of structural components. Each individual component must be safe against failure. In addition, the assemblage of components acting together must also be safe against failure. The system includes anything that is interconnected with the structure under consideration. From the soil point of view, the total system includes not only the soil beneath the structure but the soil adjacent to the structure.

The major problem arises from the fact that engineering design is generally component-oriented. The structural designer determines the size and shape of each individual component in the system. While the design codes also establish certain requirements for the assemblage of components, the interaction of those assemblages is frequently so complex that their real behavior cannot always be evaluated by the usual methods of structural analysis. Furthermore, the designer is likely to focus his attention on only those elements of the structural assembly that are his direct concern. For example, the structural engineer concerns himself directly with the structure. The mechanical engineer concerns himself directly with the mechanical system. Only rarely does the mechanical engineer consider the effect of the vibration response of the structure on the performance of the air conditioning compressor. Similarly, the structural engineer seldom considers the dynamic loading of the air conditioning equipment in his structural design. The problem of the appropriate total system becomes more complex in the foundation because the soil system that is related to a particular structure may extend beyond the limits of the building site.

Many of the engineering difficulties involving foundations result from a failure to consider certain minor, innocent-appearing components in the system or the interaction of various components of the system. For example, a small landslide occurred in a deep railroad excavation in North Carolina in spite of a design analysis based on laboratory tests of the soil that required a minimum safety factor of 1.5 against soil sliding. Moreover, the failure occurred in one end of the cut where the total cut height was substantially less than at the center of the height of the cut. The upper scarp of the slide intersected the slope well below the top. The cause of the slide was a small slickensided surface present in the residual soil mass. This minor component of the total soil structural system had not been considered in design. Although it was known that such slickensides were present, it was not feasible to determine their location nor orientation in advance. Of the hundreds of slickensides present, only one was geometrically oriented in such a way that it precipitated a slide. Thus, the failure took place although the general design safety factor was 1.5. It is likely that the failure would have occurred had the slopes been so flat that the general safety factor would be even 2.

In a second example, failure occurred because the interaction of components was not considered. A bracing system for a deep excavation in a large city was designed to support not only the loads imposed by the surrounding alleyways, but also stresses transmitted to the bracing system by an adjacent 7-story building. The design was prepared with ample safety factors, and the installation of the bracing system generally followed the best construction practice. However, at the center of the site the contractor installing the bracing encountered an underground transformer vault that had been inadvertently left off the site plans. Some of the lateral load in the adjoining building was transmitted directly through the transformer vault to the bracing system, an interaction that the design had not contemplated. As a result, a portion of the bracing system failed, causing damage to the adjacent structure.

A study of case histories thus indicates that it is necessary to consider all of the components in the total structural system, including the soil, from the standpoint of both their inter-reaction and their individual safety. From the engineering point of view it is convenient to divide the total system into two parts: the immediate system, which includes the soil and the structure directly involved, and the complementary sysstem, which includes the adjoining mass of soil as well as any structures that contribute significant loads to it.

The Immediate System

As stated, the immediate system consists of the soil and the structure directly involved in the project. Failure can occur independently in the soil, the structure, or in both. In a deep excavation for an office building, the bracing structure that supported the soil was properly designed and did not suffer damage, although the soil failed and nearly disrupted the entire system (Fig. 2). The bracing consisted of vertical H-piles acting as soldier beams, with horizontal steel beam wales supported by diagonal steel beam rakers. The design of the bracing system and the sequence of installation were shown on the contract drawings. They required driving all the H-piles and then excavating to the level of the first wale. Wood lagging was required to be installed between the soldier piles as the excavation progressed downward. At that level, the wale was to be installed followed by the diagonal rakers. Following the placing of the wale and rakers the next level of excavation would proceed. The contractor reasoned that he could change the bracing procedure and save money. He excavated a narrow slot at the location of each soldier pile and drove the soldier pile in the slot, thereby reducing the skin friction and easing the driving. He then excavated to the level of the first wale and installed the rakers. He omitted the wood lagging in this stage because it would be inconvenient and time-consuming to install it level by level. He then proceeded to excavate between adjacent soldier piles from the first wale to the bottom of the excavation. Because workmen installing the lagging would interfere with machine excavation, he planned to install the lagging after the excavation had been completed to the bottom between the adjacent soldier piles. The weather was reasonably dry, and the soil appeared to stand without the need of the lagging, which confirmed his optimism. However, after several such excavations had been made and no lagging was yet installed, a severe storm occurred. The soil adjacent to the excavation became saturated and weakened. Large chunks of earth fell between the soldier piles where the lagging should have been. Unfortunately, an 18-inch water main was supported by the soil only a few feet from the bracing system. The fallout of the soil left the water main unsupported, and it ruptured. The flow of water washed a large hole beneath the adjoining pavement of a main thoroughfare, making it necessary to close two traffic lanes.

Figure 2. Failure of soil face behind soldier piles where installation of the lagging had been delayed. The dropout destroyed the sidewalk and an 18-inch water main and undermined a 6-lane pavement.

At the same time, the flow flooded the building site to a depth of 20 feet. Nearly a month was lost in pumping the water from the site, removing the slime that had accumulated on the bracing system, and cleaning the power shovels, air compressors, and other mechanical equipment in the job. The direct cost to the contractor was nearly $100,000. Moreover, more than a month's building occupancy was lost. Even more serious was the exposure of the public to potential loss of life from the undermined street and the potential loss of property due to interruption of fire protection in the adjacent area of the city. (Fortunately, the failure took place in the early morning hours before morning rush-hour traffic had commenced, and there was no loss of life or property except from the direct loss of the pavement support.) In this case, the safety factors of the bracing system design were adequate. Because of the omission of a portion of the system, the soil rather than the bracing system failed. The contractor had not considered the safety of the soil in his streamlined operation, and as a result nearly precipitated a disaster.

Just the opposite sometimes occurs. In one project, the excavation bracing system was left to the ingenuity of an incompetent superintendent. The bracing system was an assemblage of old steel beams and wood lagging obtained from a junkyard and from the demolition of an old building (Fig. 3). It consisted of a soldier pile wall driven along the perimeter of the site and supported by diagonal rakers. No two soldier piles were the same structural shape. The diagonal rakers were old wood beams that were badly bent. There was no wale to tie the structural system together. The bracing system supported a steep bank, beyond which was a 3-story brick building. Although the bracing system was condemned by the designing engineer, the contractor delayed in replacing it with something better. Two days after its condemnation, the bracing system failed. A deep but narrow I-beam soldier pile failed by twisting. Although it was propped by a wood raker, there was no provision for lateral stability; under the pressure exerted by the soil, the beam rotated, breaking its connection with the raker. Fortunately, only a nominal wedge of soil fell out and this was partially restrained by a piece of construction equipment at the base of the excavation. The soil, therefore, generally did not fail although the bracing system did. If the soil had not been stronger than the contractor anticipated, the 3-story brick building would have dropped to the bottom of the excavation with a substantial financial loss and possibly loss of life.

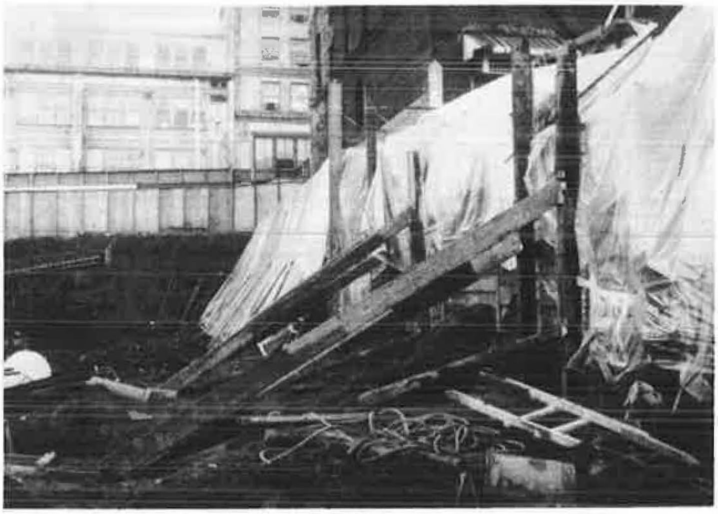

Figure 3. Poorly designed bracing system a few hours before failure.

Occasionally, the safety factor of a structure is affected by construction problems that were neither anticipated in the design of the foundation nor involved in the safety factor used in design. Thus, an unsafe structure is constructed in spite of an adequate design safety factor. An example of this type of problem in the immediate system was the construction of open pier foundations for a large office building on a site underlain by residual clay overlying limestone. The clay was approximately 20 feet thick below the bottom of the 30-foot basement excavation. Generally, the limestone was sound and the clay above it relatively stiff. However, in an elongated, narrow zone stretching diagonally across the site, the depth to rock was considerably greater than the average, and the rock contained numerous narrow slots filled with soft clay. The foundations were installed by drilling holes to the rock surface, and then installing temporary casing to support the clay. This was followed by excavation of a short socket into the sound limestone. After the hole was cleaned and inspected, it was filled at the same time the casing was pulled. In the slotted zone it was necessary to excavate far below the upper surface of the rock in order to reach sound, continuous limestone. Excavation in the slotted rock below the level of the casing was accompanied by a squeezing and flow of wet, soft soil into the socket. Large quantities of pasty soil were removed that were several times the theoretical volume of the hole. The ground surface in the vicinity of the slotted zone subsided and moved laterally toward the slot.

This movement had two serious effects. First, it generated movement of the excavation bracing system because the rakers of that system were supported by spread footings resting on the residual clay, well above the rock surface. Second, the movement of the residual clay produced lateral pressures on the pier foundations for which they were not designed. Some of the tops of the piers were moved out of their original position, and possibly some were damaged. This difficulty would not have been prevented by an analysis of the bearing capacity of the pier foundations. In fact, it is doubtful that even a ridiculously high safety factor could have prevented the movements and the foundation difficulties that occurred. It might be argued that the failures, as evidenced by the soil movement, were beneficial because they brought to everyone's attention a construction difficulty that had not been recognized by the resident engineer even though he had noted the excessive amounts of soil being removed from the pier excavations. It was only after the movements had occurred that action was taken to change the construction procedure so as to eliminate the squeezing of the soil through the slots of limestone.

The Complementary System

The complementary system includes the soil and the structures beyond the immediate limits of the project—the soil far below the level of support of the foundations, and the soil and adjacent structures beyond the construction limits. Problems in the complementary system may be reflected in damage or failure in the immediate system. In such instances the failure is not directly related to any safety factor that might have been used in the design of the structure. Instead, failure is related to external circumstances that must be evaluated in the design but are not reflected in the strength of the components of the immediate system.

The failure of a foundation caused by geologic processes unrelated to the structure or its load illustrates such a complementary failure. A highway bridge in West Florida was supported by pile foundation driven to refusal on the underlying limestone. The foundation was designed in accordance with the customary practice, and the piles were driven to provide the required support with ample safety. For years the bridge supported heavy traffic with no evidence of distress. Suddenly, two bents of the substructure dropped out of sight. Sections of the deck draped into the water, and one span was lost entirely. This occurred so quickly that automobiles traveling on the bridge ran off the open end into the water. Seven automobiles were lost and several people were drowned. This failure was apparently caused by the collapse of the underlying limestone, which supported the pile tips. Possibly, there was a thin rock arch overlying a cavity. There was enough continuing solution to enlarge the cavity or to weaken the rock until the mass collapsed. Although the bridge weight probably contributed to the extent of the collapse, there is nothing to indicate that the bridge was responsible for the geologic processes that brought about failure.

Foundation failures from erosion into underground cavities and sewers, mine subsidences, and similar phenomena involve the complementary system and are not influenced by the design safety factor of the foundations.

Occasionally, a poorly designed adjacent structure or faulty construction operation causes a failure that influences the primary structure under consideration. For example, the sudden collapse of foundations overlying cavernous limestone has been triggered by pumping water from those cavities remote from the point of failure. The lowering of the water table at one site may be responsible for serious settlement and even failure at an adjoining site. The shock, vibration, and changes in stress caused by building on one site may be reflected in changes in the soil conditions and the behavior of structures at some distance.

Failure of the structure produced by activity on adjoining sites is not always not related to the design safety factor of that structure. In some cases, ill-advised provisions to enhance the safety of the primary structure can even lead to its failure. An example of this occurred at a large country club. The club building and the adjoining swimming pool were on the top of a hill. An excavation had been made at the toe of the hill to provide a large level area for tennis courts. As a result, the slope of the hill was increased. Small landslides occurred in the slope following heavy rains. These endangered the swimming pool, although it had been designed structurally to resist some loss of support from movement in the hillside. (In this case, the increased safety of the pool saved it in spite of the continuing slides.) The club was determined to eliminate the increasing danger to the pool and directed an engineer to prepare plans for a retaining wall to support the slope. In preparing the plans, the engineer disregarded soil data showing that the hill consisted of alternate strata of sand and clay, with water under slight pressure confined within the sand seams. The design required a crib retaining wall backfilled with the "best clay-gravel" that could be obtained. The new wall was a dam that prevented the exit of water seeping through sand seams in the hillside. The pressure built up in the sand until eventually a major landslide occurred that seriously endangered the swimming pool and destroyed the very wall that was designed to protect the pool.

The complementary system, therefore, must be considered vital in the ultimate safety of any structure, even though the effects of the complementary system cannot be expressed in terms of a simple safety factor of the structure.

NONFAILURE

Failure of a structure may be caused by movement within some portion of the system that is not related to a failure of that portion of the system. The elastic deflection of the soil in the face of a braced excavation that causes settlement of the adjoining structures is a good example of such a nonfailure producing a failure. In one such case, the excavation for a new office building was within 8 feet of the outside wall of an old brick wall bearing structure. The contractor for the office building concluded that the old brick structure was too weak to withstand underpinning. Therefore, he undertook to protect the old building, its foundation, and the soil supporting its foundation by a strong bracing system. This was a reasonable solution because the foundation level of the old structure was not far above the ultimate excavation line of the new building. The bracing system consisted of interlocking concrete cylinders, installed by augering holes and filling them with concrete with appropriate reinforcement. The upper ends of these cylinders were supported by diagonal rakers, resting on foundations within the new building site. Shortly after the excavation was complete, movement was noted in the foundations of the old building. The foundation settled slightly and moved laterally toward the excavation about ½ inch. An analysis of the bracing system showed that the safety factor was adequate. However, it was necessary for the bracing system to deflect in order for it to mobilize any resistance to lateral movement. The bracing system (including the soil, the vertical interlocking cylinders, the steel rakers, and their foundations) absorbed considerable movement before their resistance was mobilized. Although the movement was sufficient to cause damage to the adjoining structure, the elastic deflection was unrelated to the safety factor of either the new building, the bracing system, or the old foundations. Failure could have been prevented by prestressing the bracing system to minimize deflection.

Consolidation of the soil is another factor in damage caused by nonfailure. Ordinarily, the abutment of a bridge that acts as a retaining wall to support an approach fill is designed to resist active earth pressure. The earth pressure causes the abutment to tilt outward away from the fill, a movement necessary to produce the active pressure. However, such a fill is frequently placed above a weak, compressible soil. In one instance, the consolidation of the compressible soil under the weight of the bridge caused the abutment to tilt away from the bridge far enough that the approaches had to be reconstructed. Equally serious is the effect of the movement on the earth pressure. The active earth pressure used on design presumes a small outward tilt of the abutment. The inward or reverse tilt could raise the pressure and create loads for which the abutment was not designed.

A subsidence produced by environmental changes is another form of nonfailure that is not related to the foundation safety factor. Yet a subsidence can cause a structural failure of major magnitude. Changes in the groundwater level produced by long-term changes in climate or by drainage that accompanies construction in large cities cause increased effective soil stresses and consolidation of soil strata. Although the most susceptible layers are clays, such consolidation settlements do occur in sand and silts.

Rapid fluctuations in the water table in a coastal city produced severe settlement cracks in a church that had no signs of distress for the first 50 years of its life. A long-term dry spell accompanied by drainage of a deep excavation nearby, followed by several periods of very wet weather, caused severe changes in the water table and subsidence of the heavy load-bearing walls of the building and accompanying cracks.

Drainage-induced consolidation frequently accompanies deep excavations that require well-pointing or other forms of accelerated construction drainage. The drawdowns associated with shallow wells sometimes produce settlement in adjoining structures. Occasionally, the rapid drawdown accompanying high rates of well pumping induces such severe gradients that seepage erosion occurs. The settlements in such cases are likely to be sudden and disastrous. The erosion-induced subsidence in this way differs from the progressive settlement produced by the effective stress increases resulting from drainage.

Poorly compacted backfill adjacent to bridge abutments and around drainage structures is a frequent cause of delayed settlement in highways. The loose soil when dry may be relatively strong and incompressible. When it becomes inundated because of changes in environment the hard lumps soften and rapid settlement takes place. Settlements of several inches to several feet are not uncommon in poorly compacted dry backfills. Dropouts in pavements above uncompacted utility trenches are common in nearly all cities. Such settlements occur rapidly, immediately after the change in environment. The damage resulting from such settlement is not directly related to the safety factor of a foundation or pavement supported on the compacted fill. Instead, the subsidence and resulting damage take place regardless of the safety factor. It is frequently difficult to differentiate between such subsidences and the rapid downward movement produced by a bearing-capacity failure. Where a foundation is directly supported by a dry, poorly compacted soil, the weakening of the soil upon inundation also could produce a bearing-capacity failure. The safety factor required to insure against such a failure due to soil softening upon inundation would be excessive, however.

BENEFICIAL FAILURE

Although failure is generally considered to be bad, some "failures" are beneficial. For example, the driving of pile requires successive bearing-capacity failures in order to advance the tip of the pile through the soil strata. Although successful driving of the pile requires failure of soil, it must not produce failure of the pile shaft. During driving the safety factor of the soil will be 1; the safety factor of the pile shaft at the same time must be sufficiently greater than 1 so that the pile shaft does not fracture under the hammer impact. The completed pile, therefore, must represent an unbalanced design with the pile shaft having a greater safety factor than the soil surrounding the pile. This has been ignored by some engineers, who have attempted to make a balanced design with all the safety factors equal. The result has been damage to the pile shaft during driving.

Certain engineering analyses require soil failure as a part of the ultimate design. For example, the design of a retaining wall for active earth pressure requires that the soil behind the wall fail in shear sufficiently to mobilize the strength of the soil. The wall, on the other hand, must have a safety factor large enough that it will not fail or move inordinately under the reduced pressure developed through soil shear. Paradoxically, it also requires that the wall be able to deflect enough under the loads produced by the failing soil that sufficient shear is developed to establish the active state. When this deflection of the wall is ignored, enough cracking and local failure will develop in the wall structure so that the required movement can occur. In this case, the wall may not necessarily be really failing; instead, it is moving as required by the design assumptions. The movement is frequently accompanied by cracks in the soil mass behind the wall, causing alarm to all concerned. If a structure is placed on the wall before the backfill is complete or if a structure's foundation is placed in a lower part of the backfill before the backfill is complete, the structure will move with the shearing soil and will suffer damage. In such a case, the circumstances include a beneficial failure in the soil accompanied by required deflection in the retaining structure but producing a damaging failure in an adjoining structure. In this case, an additional safety factor in the design of the foundation placed in the backfill or a structure supported on the wall could not prevent its movement and damage.

Occasionally, a failure is beneficial in that it gives warning of serious trouble that is developing or provides a safety valve that prevents further failure. A highway fill placed on hillsides underlain by water-bearing strata of sand can act as a dam and cause the water pressure to build up in the blocked strata. If the water pressures are great enough, the soil strength will be reduced until it is less than the stresses imposed and failure follows. If the failure involves the movement of the embankment, it may uncover the blocked stratum and allow drainage. In one such case, a large highway embankment slid down a mountainside after a clay fill prevented drainage from thin seams of jointed sandstones sandwiched between impervious layers of shale. The failure continued for several years as additional clay fill was placed over the pervious seam in order to keep the roadway at the proper elevation. Finally, someone hit on the idea of maintaining the roadway elevation by a pervious fill. The continuing movement of the embankment down the hill combined with refilling eventually brought the new pervious fill to the level of the water-bearing stratum. Thereafter, the rate of movement was much slower.

THE OVERALL VIEW

The Illusion of Safety

The foregoing discussion illustrates the problems associated with establishing safety factors for design. Too often, the safety factor is an illusion—an imaginary crutch that helps the designer over the difficult point of evaluating the unknown forces, the uncertain resistances, and the inevitable inaccuracies of engineering analyses. Unfortunately, the continuing use of safety factors without their accurate verification by detailed studies of failures can lead the engineer to the illusion that the numerical value of the safety factor is a real measure of the margin of safety of the structure. The illusion becomes a deception when the engineer is pressured into reducing the safety factor because of economic considerations or because other design disciplines (which confirm their real safety factors by pilot tests of full-scale models) can get by with lower safety factors as well as an occasional failure. The aircraft industry can afford to use a small safety factor because it checks the overall safety factors by test flights. The occasional inadequacy of the original safety factors is demonstrated by the fact that test pilots are very well paid and by the fact that sometimes aircraft must be recalled for modification after a rash of failures shows some deficiency.

The engineering profession must recognize that a computed safety factor greater than 1 does not insure safety. Moreover, a computed safety factor somewhat less than 1 does not necessarily mean that failure is inevitable.

The Elusive Nature of Safety

The safety factor is elusive because many of the factors that contribute to the safety of a foundation cannot presently be evaluated with accuracy. This elusive aspect of safety has led to a probability approach wherein the safety factor is related statistically to the reliability of the test data on the strength of the material, the reliability of the loading, and the probable errors in the computations. Such a probability approach is reasonable in manufactured products where the possibility of failure can be tolerated and where the cost of failure versus the value of safety can be evaluated statistically. However, the statistical possibility of failure of a major engineering structure, such as a dam, cannot be evaluated. In the first place, a statistical analysis becomes unreliable at the extremely low probabilities that must be considered in such a design. Furthermore, there is every reason to believe that there are upper limits for the forces that might be involved in engineering problems, whereas statistical analyses consider that even an unreasonable magnitude of force is statistically possible. The statistical approach, therefore, is appropriate only to those loads that occur frequently enough that a valid statistical analysis is possible. Until enough failures can be analyzed that a valid statistical analysis is possible, a statistical evaluation of safety will be impossible.

The admission of possible failure implied by statistical analysis raises a question of public response. The public apparently is reasonably content to deal with the statistical possibilities of individual accidents. The statistical possibility of the failure of a bridge or dam in a populated area, however, is probably inadmissible.

THE COMPONENT APPROACH

An interesting approach to the safety factor was suggested by Brinch Hansen in 1961 (1). He proposed varying safety factors to be applied to the loads acting on the structure as well as to the various soil properties used in analysis. (He did not consider the use of a safety factor to compensate for inaccuracies in analysis, however.) For the dead load on a structure he proposed a safety factor of 1.0 because the dead load should be capable of precise evaluation. For design, live load should be increased 50 percent to allow for unknown variations. For groundwater loads, the increase should be 20 percent. The author cannot agree with the latter recommendation because water loads can involve a greater degree of unknown than other live loads unless there are physical limits to the level to which the water can rise.

Safety factors are also applied to the components of soil strength individually. The apparent cohesion of a clay soil is divided by a number ranging from 1.5 to 2, depending on the accuracy of the soil tests and the sensitivity of the material. The tangent of the angle of internal friction (or factors derived from the angle of internal friction) is reduced by an amount equivalent to dividing the tangent of the angle of internal friction by 1.2. This is considered reasonable, because the range of the angle of internal friction in most soils is rather limited. It is the author's opinion that this approach is sound but that additional components of safety factor are necessary because of the uncertainties in the accuracy of the engineering analyses that are used.

THE EMPIRICAL APPROACH

Because of the illusory and elusory nature of the safety factor, the shortcomings of the statistical approach, and the uncertainties in the accuracy of engineering computations, the author prefers the traditional empirical approach of an overall safety factor developed from experience. Most practicing engineers utilize a safety factor derived from their own experience. After years of experience it is possible for the engineer to determine if that safety factor is inordinately low by the incidence of failure resulting from his designs. If he has no failures, he may congratulate himself that his safety factors have been adequate; on the other hand, he may merely have been unduly conservative.

A proper use of the empirical approach requires that there be a full study of all failures that occur so that the source of the error, if any, can be pinpointed and the uncertainties involved in loading, evaluation of resistances, and engineering analyses can be established. While such postmortems are embarrassing to those directly involved, such failures are the chief source of full-scale tests. Occasionally, the engineer is given the luxury of making a full-scale test of a structure, loaded so as to produce failure. When such an occasion arises, the engineer is professionally obligated to study that failure extensively and to make the results of the failure known to the profession. More often, the study of controlled failures is limited to models. Frequently, the models are so small that extrapolation of their results to full-scale structures is questionable, if not hazardous. Properly conducted and thoroughly evaluated large-scale tests, however, offer much promise in determining what the safety factors ought to be for engineering design. Unfortunately, in new situations the engineer is still confronted with a lack of empirical data and adequate analyses. In such cases he must rely on his intuition and good fortune.

Failure is a risk inherent in all endeavor, whether it be the design and building of an engineering structure or stepping across a crowded city street. The risk of failure can be eliminated only be eliminating endeavor itself. Unfortunately, the growing number of lawsuits filed against engineers in cases of failures or near-failures will only lead to more conservative and expensive designs and a stifling of initiative in new engineering developments. This will be a disaster for the engineer as well as for society.

The alternative is for society as well as the engineer to face the fact that engineers are not infallible and that failures occasionally occur in spite of the best designs. The risk of failure must be pointed out to those who request such designs and ultimately the owner and society as a whole must accept the responsibility for the risk rather than the designer, because ultimately the owner (and society) must bear the responsibility for the risk of failure, since they reap the benefit for the greater chance of success.

The engineer is obligated to minimize the risk by using his best talents with the most advanced engineering knowledge suitable to the task. He then must acquaint the owner with the possibilities of failure and the possible consequences. The owner is obligated to weigh these against the value of the completed structure. Only when the risk of failure is faced honestly by all concerned can proper designs be evolved.

Absolute safety is a myth. A quantitative statistical evaluation of safety is not technically feasible when enough full-scale failures to establish a valid statistical analysis cannot be tolerated. Instead, the profession must rely on its intuition and experience and make use of the knowledge gained from a full investigation of every failure that presents itself. Such a program can lead to more reliable safety factors as well as lower safety factors and cheaper structures, but rapid changes are not likely.

REFERENCES

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