Safety and Factors of Safety in Trench Construction

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Soil trench cave-ins have been and will continue to be a major construction hazard. Present state and federal legislation is shown to be inadequate by example calculations of safety factors and reference to known soil behavior. Specifically, the term "angle of repose" referred to in most codes is shown to be meaningless and dangerously misleading. Methods used in current research on this problem in Iowa are described.

•SOIL TRENCH cave-ins have always been a construction hazard. With present-day concentration on water pollution control, increased demand for housing, and more federal aid for projects of this nature, the possibility of this hazard is even more pronounced. There were five deaths resulting from trench cave-ins in Iowa in the fall of 1967. All occurred in two accidents in a small town receiving federal aid to install a municipal sewer system. Nationally there were at least 125 similar deaths during the two-year period ending June 1967, as reported by Land (1). As a result of the Iowa tragedies, a soil trench cave-in accident study has been sponsored by the Engineering Research Institute at Iowa State University. At the time of four of the Iowa deaths, a new "safety rule for excavation" (2) had had the effect of law for 39 days. The rule was ineffective in preventing the cave-ins, and because of its inherently weak terms and penalty provisions probably would have been so regardless of its age. Pressure is being exerted on the state legislature to stiffen the requirements and penalty provisions of the law. Four cave-in deaths in Nebraska (3) in the spring of 1968 will probably have the same effect on the Nebraska state law governing excavation. Both the Iowa and Nebraska laws appear to suffer from a lack of teeth. Unfortunately, most laws and codes not only lack adequate means of enforcement but are inherently defective.

A soil trench cave-in failure is imminent when the fully mobilized shear strength on the weakest plane in an embankment is just equal to the shear stress on the same plane. It is assumed that the strains in the embankment are large enough to fully mobilize cohesion and frictional resistance before failure occurs. If the strains are not large enough, or if tension exists anywhere on the failure surface, then progressive failure is probable. In a progressive failure situation, localized failures occur at overstressed sections along the main rupture surface in a sequential fashion as opposed to one single failure. Sowers (4) indicates that a progressive failure situation exists in most instances that exhibit three signs. The first sign is subsidence of the adjacent ground surface. The second sign is the formation of tension cracks parallel to the trench. The final indication is the spalling of small pieces of soil from the cut face.

Analysis of progressive failure is extremely difficult, and current practice calls for an adjustment in the factor of safety to provide for this eventuality. The factor of safety as used in slope stability is normally arrived at by applying a factor to one or both components of the soil shear strength. If the factor of safety is with respect to shearing strength, then the same factor is applied to both the cohesion and tangent of the internal friction angle. If the factor of safety is with respect to cohesion, it is defined as the

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ratio between the actual cohesion and the cohesion required for stability with full friction mobilized. The latter is also called the factor of safety with respect to height, and is most frequently used for slope stability analysis.

Terzaghi (5) gives several equations for analyzing vertical slopes with inclined plane rupture surfaces. The critical height is given as

$$H_c = 4 \frac{c}{\gamma} \tan\left(45 + \frac{\phi}{2}\right) \tag{1}$$

where c is the cohesion, γ is the unit weight of the soil, and ϕ is the internal friction angle. The inclined plane slopes up from the ditch bottom at an angle of 45 + (ϕ/2) degrees with the horizontal. When a trench is cut in the soil a state of tension exists in the surface soil adjacent to the ditch. In time, vertical tension cracks develop parallel to the edge of the ditch. The depth of the cracks and the distance back from the edge of the ditch is about half the depth of the ditch. The length of time necessary for the cracks to occur varies but is probably a matter of hours. The cracks may be considered a step in a progressive failure. The critical height after the tension cracks have developed is

$$H'_c = 2.67 \frac{c}{\gamma} \tan\left(45 + \frac{\phi}{2}\right) \tag{2}$$

If surface water accumulates in the cracks, a hydrostatic pressure is exerted on the crack wall and the critical height is further reduced to

$$H'_c \cong 2 \frac{c}{\gamma} \tan\left(45 + \frac{\phi}{2}\right) \tag{3}$$

The reduction of the critical height caused by water in Eq. 3 results solely from the pressure of the water within the crack. If the soil becomes saturated then a further loss in stability occurs.

Consider as an example a particularly dangerous Iowa soil (6) with cohesion of 1.3 psi, a unit weight of 90 pcf, and a friction angle of 25 deg. Assume a ditch is to be dug 6.0 ft deep. What is the factor of safety?

Many factors of safety can be expressed, depending on the method chosen for defining the factor and the circumstances surrounding the excavation. Using Eqs. 1, 2, and 3 and the data given, the calculated critical heights are 13.1, 8.7, and 6.5 ft, respectively. The corresponding factors of safety with respect to height are 2.2, 1.5, and 1.1. If the soil is saturated by surface or ground waters a further reduction in the critical height can result from a loss of cohesion or from seepage pressures. The soil in the above example has a cohesion of 0.3 psi when saturated. Using the same equations and conditions as previously cited except for the reduced cohesion, the critical heights are 3.0, 2.0, and 1.5 ft respectively. The factors of safety with respect to height are correspondingly 0.5, 0.33, and 0.25. If seepage pressures are taken into account, a further reduction in stability results. A reduction of the cohesion from 1.3 to 0.3 psi is a reduction of 77 percent. Equal reductions in the critical heights and the factors of safety with respect to height are observed; i.e., 13.1 ft to 3.0 ft and 2.2 to 0.5 are 77 percent reductions. The friction angle remains the same and the frictional resistance is fully mobilized in all cases. As noted earlier and as shown above, the factor of safety with respect to cohesion is the same as the factor of safety with respect to height.

The factors of safety above could have been given with respect to shearing strength where the cohesion and tangent of the friction angle are reduced equally. For example, in the first calculation the factor of safety with respect to cohesion or height was 2.2; had it been with respect to shearing strength it would have been 1.8. Factors of safety with respect to height are used in slope stability analysis because of simplicity and ease of calculation.

The Iowa law states, "The sides of all trenches which are six (6) feet or more in depth, and where the earth is not sloped to the angle of repose, shall be securely held by shoring." Nearly all slopes of trench walls are being considered, if not accepted, as the angle of repose. Unfortunately, since the angle of repose does not exist in most cases, this section effectively negates whatever usefulness the law might have had. Although Iowa law indicates 6 ft, most laws of this nature require shoring for depths over 4 ft. In any case, specifying constant depth for shoring without regard for soil or circumstance is improper.

The preceding paragraph closely resembles the American Standards Association statement (7): "The sides of all trenches which are four (4) feet or more in depth, and where the earth is not sloped to the angle of repose, shall be securely held by timber bracing. The bracing shall be carried along with the excavation and must in no case be omitted unless the trench is cut in solid rock or hard shale." The National Safety Council (8), although having published a superior document with respect to cave-in problems, also speaks of the angle of repose. None of the codes or recommended specifications contained a definition of the angle of repose.

Terzaghi (9) states in a letter, "There is no such thing as an angle of repose of cohesive earth." Later in the same letter Dr. Terzaghi says, "For perfectly clean and dry sand or gravel the angle of repose is fairly independent of the heights of the heap and the method of dumping, and it is approximately equal to the angle of internal friction of the sand in the loosest state. The angle of repose of moist sand and of cohesive soils depends essentially on the height of the heap and on the method of dumping. Hence, in connection with such soils, the angle of repose has no meaning."

Although the angle of repose does not exist for cohesive soils, sloping trench walls as an alternative to shoring is sound engineering. The actual slope must be determined by acceptable theories tempered with appropriate factors of safety. Several design methods for determining safe slopes are available and the choice depends on the general steepness and height of the slope, complications resulting from adjacent structures and boundary conditions, and general soil conditions. For steep banks such as found in trench construction, the Culmann solution (10), which is the more general solution of Eq. 1, is probably acceptable. The safe height is

$$H = 4 \frac{c_d}{\gamma} \frac{\sin i \cos \phi}{\left[1 - \cos\left(i - \phi_d\right)\right]} \qquad (4)$$

where c_d is developed cohesion, ϕ_d is the developed friction angle, and i is the slope of the trench wall with respect to the horizontal. The parameters c_d and ϕ_d were determined by dividing the actual cohesion and tangent of the friction angle by a factor of safety with respect to shearing strength. The Culmann method is justifiably criticized because of the assumed plane rupture surface, and even though the soil and water conditions are known and accounted for, a factor of safety with respect to shearing strength of at least 2.0 should probably be used (11). In any case, it becomes readily apparent that any statement calling for an angle of repose in a cohesive soil is meaningless.

Another section of the Iowa law states, "Excavated material and superimposed loads shall not be placed nearer than eighteen (18) inches from the sides of the trench, unless bracing has been installed of sufficient strength to withstand the load." This statement is the same as the American Standards Association statement except the latter ends as ". . . installed and designed to withstand the load." A similar statement from the National Safety Council is as follows: "The amount of soil to be removed as well as the nature of the soil structure will determine how far back from the edge of the trench the soil must be piled. Excavated material and other superimposed loads should never be placed nearer than 18 in. from the sides of the trench. It is, however, good practice to allow at least 24 in. to prevent rollbacks. When superimposed loads or equipment are within the limiting plane of rupture, timbering must be increased to withstand the resultant additional pressures."

Once again the National Safety Council seems to have the superior document. The Iowa law appears to be ambiguous and the intent of the statement is questioned; either it was meant to prevent rollbacks or to provide for surcharges. In either case the implication is that there is no danger resulting from surcharges, regardless of the depth of the ditch, if the loads are kept back 18 in. This is not the case. For example, in the first sample calculation where the ditch was 6.0 ft deep and Eq. 1 was used, the factor of safety with respect to shearing strength was 1.8. If a 400-lb per lineal ft surcharge is placed anywhere within 4.5 ft from the edge of the ditch, the factor of safety with respect to shearing strength drops to 1.5. Designing for loads "within the limiting plane of rupture" is much more meaningful than attempting to specify some specific distance for all cases.

The First National Conference of States on Building Codes and Standards (12) was held at the National Bureau of Standards in May 1968. Former Illinois Senator Paul E. Douglas in his keynote address stressed the urgency for uniform building codes. Douglas said, "Local building code regulations are a major obstacle to true low-cost housing." Gene A. Rowland, chief of the codes and standards section of the National Bureau of Standards, indicated that existing codes are "not bad," but rather "too much of a good thing." Douglas also said, "If the states do not find a way to get around unduly restrictive building codes, we'll have a national code. If you don't clean house, the federal government will."

Building codes are drafted to satisfy minimum standards of performance and safety. However, the right to choose the system that will satisfy the intent of the code must not be infringed upon. For economic reasons, if not other, the innovator must be free to create new systems for accomplishing the given task as well as to improve current procedures.

Engineers have not been active in the past in developing the majority of these codes. However, if the engineer does not become active and make decisions in this field, then someone else, perhaps not so well versed in the problem, will do so. The end result will be engineering by a political group with safety in mind and with little thought given to engineering economics, alternatives, or innovation.

There are diverse opinions as to what role the engineer should play in the soil trenching field. The prevailing opinion appears to place all of the responsibility with the contractor. Under this system, when a job is advertised the contractor takes his own borings, determines what difficulties he is to encounter, and submits his bid based on this information tempered by his past experience. At a recent ASCE section meeting, one contractor on a panel discussing trench excavation indicated that the engineer should furnish only enough information for the contractor to find the job.

While the preceding has probably been at least partly true in the past, Greer and Moorhouse (13) indicate that the standards of the profession are changing. It is time the engineer recognized and accepted his responsibility in subsurface construction. If the engineer makes a complete and proper study, he need not attempt to protect himself with a disclaimer, but will be in a position to supply prospective bidders with sound information. This information, because it removes doubt and duplication of effort, will eventually, if not immediately, lead to more economical and safer construction projects. This is far better than an uneconomical iron-clad code that is safe under all circumstances, in all soil types, at all times, or, because of its ambiguity, places the contractor at the mercy of the individual interpreting the law.

Early results from the Iowa State University study indicate that Terzaghi's solution for the stability of a vertical bank weakened by tension cracks is probably satisfactory. Only a limited number of observations are available, but Eq. 2 has proved satisfactory in evaluating cave-in failures. In Iowa, a field trip is made to each significant failure site in the state as it is reported. Close cooperation with the Iowa Bureau of Labor, whose field inspectors report the failures, makes this arrangement possible. Field strengths are evaluated with the newly developed bore-hole shear device (14).

Other objectives of the Iowa State study are to investigate the effects of time on the stability of trench walls, the effects of surcharge loads, vibrations, moisture content variation, ditch geometry, and construction procedures. All of these effects must be recognized either directly or indirectly through the factor of safety. Eventually, a manual of recommended practice for trench construction in Iowa soils will be published.

Stronger and more uniform national and state building codes are being demanded. If the engineer is to have a hand in drafting codes and specifications and is to furnish direction to his clients and to contractors, then he must have reliable information. Knowledge of this type can be gained only through thoughtful study and research. The engineer must act now, however, before national and state codes are written and rewritten by those less able to do the job.

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Discussion

TERENCE J. HIRST, Assistant Professor of Civil Engineering, Geotechnical Engineering Division, Lehigh University—The author is to be congratulated for drawing the attention of engineers to problems surrounding establishment and enforcement of safe and economical building codes. Once again we are faced with evidence of society's inability (or refusal) to act on behalf of individual safety until after tragedy has occurred.

The various safety factors that the author computed for a vertical cohesive embankment dramatically illustrate the meaningless nature of such factors unless each is accompanied by information concerning the method of analysis, the soil properties, and the assumed boundary conditions. For example, the factor of safety with respect to cohesion is not the same as the factor of safety with respect to shearing strength. Because the conditions necessary to the development of cohesion and friction are not clearly understood, it is difficult for the discussant to understand the rationale behind determination of a safety factor with respect to cohesion rather than shearing strength, particularly since the latter is numerically lower than the former.

Most of the currently acceptable methods of stability analysis employ a failure mechanism such as a plane or circular surface of sliding in conjunction with limit equilibrium. In an effort to provide additional insight into the validity of existing limit equilibrium analyses, research at the Fritz Engineering Laboratory at Lehigh University has been directed toward establishing alternative solutions to stability problems by assuming that the embankment soil behaves as a perfectly plastic material. Preliminary results suggest that, for the special case of vertical cohesive embankments, the use of limit equilibrium in conjunction with a plane surface of sliding yields critical heights similar to those obtained from an analysis that assumes plastic behavior and a logarithmic spiral surface of failure. However, such agreement is not evident for embankments whose slopes are not vertical.

Other factors, additional to those noted by the author, must be considered when investigating the stability of cohesive embankments. For example, the properties of cohesive soils are known to be time-dependent. Although it might be argued that most trenching operations are of short duration, a significant number of trenches do remain open for long periods of time, thus necessitating consideration of the influence of time on the soil properties. Indeed, the current state of the art does not provide the engineer with an economical means to measure appropriate soil properties or to perform comprehensive stability analyses for each soil type encountered in every trench.

In summary, although supporting the author's dislike of uneconomical iron-clad building codes, the discussant suggests that replacing existing arbitrary codes with oversimplified methods of analysis may lead to equally meaningless requirements similar to those currently established. Until there is a better understanding of all of the variables affecting stability analyses, an uneconomical, arbitrary—but safe—code is perhaps more attractive than a code based on a method of analysis that yields a safety factor of dubious reliability.