FEATURE

Back-analyses of Slope Failures to Derive Strength Parameters in the Ground

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The current state of knowledge in the engineering fraternity has undoubtedly been developed through destructive testing of engineering elements.

Engineering systems are frequently evaluated in miniaturised dimensions and the outcomes then extrapolated and scaled up to life-sized constructions. Prototype tests to failure have also been undertaken but they tend to be few and far between, owing to time and cost considerations.

So whenever a real-life construction failure occurs, engineers will grasp at the opportunity to treat it as a prototype scale test and subject it to back-analyses (forensic engineering activities) to unravel the governing cause for the distress as well as attempt to push back the frontiers of knowledge. This will include the estimation of material strengths prevailing at the instance of failure.

Earthworks engineering is no exception. It has had its share of such treatment as seen in Bjerrum (1972) and Skempton (1964). These two landmark publications marked the emergence of serious efforts at attempting to understand the likely operational strengths in the ground at the instant of structural failure.

In particular, Skempton (1964) demonstrated, from a very long time back, that mobilisable shear strengths during slope failures were less than peak values obtained from element tests on soil samples in the laboratory. Likewise, Bjerrum (1972) also showed that peak undrained shear strengths were not available in soft ground foundations supporting embankments.

Strengths of materials prevailing in the ground are especially desired when it comes to the design of remedial works following failures of structures that supported the ground.

A deficiency with the evaluation of earthworks structural stability lies with engineering practitioners' discomfort in reconciling field and laboratory tests with the processes occurring at the instance of a failure. Such deficiencies could not be addressed until the mechanics of soils founded on effective stress was developed and understood.

Though the considerably more comprehensive framework of critical state soil mechanics was released to the world vide Schofield and Wroth (1968) its acceptance was hesitant at best, even today. This allowed the preservation of a "mystical aura" in geotechnical engineering which sustained the inability to relate elemental tests to field behaviour and encouraged empiricism in geotechnical engineering practice.

This discussion concerns the employment of the back-analyses to derive engineering parameters following failures of earth structures. It is limited to problems of stability owing to gravity forces alone, namely slopes. These may be cut slopes or slopes of embankments built over competent foundations. Such problems involve the least complexities as far as shear strength variation specifications are concerned as opposed to stability evaluations involving soft ground foundations.

A compelling reason to establish reliable strength parameters for use in earthworks engineering analysis and design, lies in the fact that a very low reserve of strength against collapse is targeted. This is despite the rather inexact analysis methods available. The widely adopted guidance GCO (2000) recommends a Factor of Safety (FoS) of only 1.4 in a 10-year return period rainfall for the highest risk-to-life category of earthworks. For slopes deemed to have lesser risk-to-life consequences, the FoS is an even lower 1.2. Such a magnitude of strength reserve against collapse is by far the lowest employed for civil engineering constructions.

When deployed with a set of unrealistic and optimistic shear strength parameters for the ground, the true reserve for stability may be smaller than envisaged or worse, not even in existence. It should be noted that GCO (2000) does not specify what shear strength parameters should be used.

1.0 ANALYSIS METHODS

The Limit Equilibrium Method is the oldest available procedure for the analysis of stability of slopes for design and it is by far the most popular and convenient to use. A second method of greater sophistication and capability is the Finite Element Method. Today, both methods are complemented by very capable pre-processing and post-processing facilities, making them easy to operate. But use of the Finite Element Method is rather limited as it demands a deeper understanding of engineering mechanics and numerical modelling from the user.

1.1 LIMIT EQUILIBRIUM METHOD

The Limit Equilibrium Method (LEM) utilises the principle of static equilibrium and computes the FoS provided by the resisting capacity of the ground against the destabilising gravity forces. The problem geometry is divided into a pre-selected number of slices and the collective static equilibrium evaluated for each pre-defined analysis geometry. A large number of geometries has to be dealt with in order to arrive at the likely FoS for a particular problem, the lowest computed FoS being the one of interest.

There is a large number of LEMs available and most of these have been incorporated into software codes and available commercially. The principal differences between the various methods lie in whether stability is evaluated using moment or force equilibrium or both, as well as in the way the inter-slice forces are addressed. Solutions based on moment equilibrium are less affected by inter-slice forces assumptions.

Naturally, varying results will arise from the different LEMs used for an identical problem. The more comprehensive methods satisfy both moment and force equilibrium together with the treatment of inter-slice normal and shear forces included.

But the LEM solution can be fraught with inadmissible physics particularly associated with the treatment of side shear forces on the sides of slices while still providing a seemingly reasonable answer. Whitman & Bailey (1967) discusses this problem in great detail and concedes that ground with multiple soil stratifications will make it very difficult to evaluate the validity of a LEM analysis.

1.2 LEM SUPPLEMENTED WITH STRESS ANALYSIS

A hybrid procedure is promoted in Krahn (2003) where the normal stresses at the base of slices are predetermined from a finite element analysis and then imported for use with the LEM.

This offers the advantage of capturing the relevant kinematic features of a problem along with a more representative distribution of stresses along a shearing surface, thereby allowing the LEM to arrive at the solution with a larger lower bound. As the stresses are obtained from a continuum analysis, it obviates the need to arbitrarily specify inter-slice side force functions and therefore, relieves the need to check for validity of the location of the line of thrust on each slice.

Krahn (2003) suggested that even the use of the simplest linear elastic material model with the gravity turn-on technique applied after the creation of the problem geometry, would be sufficient to allow the LEM to yield a superior analysis. His examples of computations employing stresses imported from finite element analyses, all showed higher FoS than those made solely from LEM analyses, as would be expected.

But it should be cautioned here that there exists the danger of erroneously high lower bound solutions resulting from unrealistic stress analyses especially where material stratifications with very large stiffness differences are present.

1.3. FINITE ELEMENT METHOD

The forte of the Finite Element Method (FEM) in an engineering analysis lies in its ability to compute deformations. It is able to couple with highly refined constitutive stress-deformation soil models to accomplish this. To arrive at the FoS against failure used in the same context as the LEM, the shear strengths in the modelled ground are reduced progressively until failure is obtained in the analysis. Zienkiewicz et al. (1975) offered the first publication on this procedure. The smallest reduction factor that results in failure is then declared the FoS.

While the FEM offers a number of advantages over the LEM in terms of realism with stress analysis, it does require more input descriptors than the latter and makes the former more formidable to conduct. Griffiths and Lane (1999) gives a good account of the technique. Stress and deformation compatibility is assured throughout the body of the problem being evaluated. Its validity will be greatly dictated by the choice of material stress-strain model(s) used and whether the geological and constructional processes that lead to the formation of the ground geometry being evaluated have been reasonably replicated.

Structural failure in FEM analysis is commonly taken to occur when the analysis is unable to converge to a solution. But as Krahn (2003) pointed out, the FEM analysis may display the inability to converge for reasons other than structural failure, so the method can readily lend itself to spurious outcomes.

In the back-analysis on a slope collapse, the FEM analysis has to start with the problem already with the non-convergence condition so it will not be able to yield a valid set of stress distribution results for use in the hybrid LEM analysis. This leaves the conventional LEM available for back-analysis.

2.0 THE BACK-ANALYSIS

The analysis for determining the structural stability of any earthworks construction is mostly made using the limit equilibrium approach. This would require the following input parameters to be known for a particular ground geometry, namely,

1. cohesion, c'
2. soil friction angle, ϕ'
3. bulk density, γ
4. pore-water pressure, u_w.

In a back-analysis of a collapsed slope, this would mean the need for 4 basic variables to be specified for each soil stratification. The strength parameters sought usually are c' and ϕ' though in rare instances, the water pressure regime is sought (MPAJ, 1994). They can exist in many very significant permutations especially when multiple soil stratifications are present.

The back-analysis process is invariably made by invoking the FoS of the failed construction as unity and then iteratively determining the parameters that collectively satisfies this. As previously noted, the back-analysis is not likely to enjoy the availability of a set of stresses from a prior FEM analysis.

In routine design application, being a Lower Bound class of solution, the LEM produces a conservative estimate of stability for the strength parameters used. So a back-analysis employing this procedure will yield a set of higher strength parameters than may actually prevail in the ground at collapse.

Chandler (1977) reported back-computed values of up to 10% higher than laboratory test values in spite of working with the "maximum observed pore water pressures". His laboratory test strengths were the residual values to reflect observed the landsliding on pre-existing shear surfaces.

3.0 MATHEMATICAL VALIDITY OF BACK-ANALYSIS

Any back-analysis, by whatever means on a single failure geometry, amounts to little more than an attempt at solving a single mathematical equation. This naturally permits no more than just a single unknown quantity to be solved for whenever a back-analysis is conducted.

In most cases, each slope failure involves construction with the same single geometry. This affords just a single back-analysis to be conducted when a failure occurs. The same is likely to prevail with landslides in natural slopes, commonly taking the form of reactivated slides.

Leroueil and Tavenas (1981) advocated that failures in the same ground, with as many different geometries as possible, must be analysed in order to arrive at a set of valid strength parameters for the ground. But they still expressed doubts as to the accuracy of the back-analysis since exact pore water pressure conditions at the instant of failure and, in particular, its variation along the failure shear surface, was unknown. They further stated that a back-analysis cannot be reliable when some key input data to the analysis has to be explicitly assumed which invariably is unavoidable for most instances.

Chandler (1977) cautioned that the outcome from a back-analysis can only be validly used when the data is used in the subsequent analysis where the geometry of the landslide being analysed is not radically changed by the ensuing remedial engineering works. Further, considering that different LEMs will give rise to different results, the back-analysed strengths should only be subsequently used with the same LEM that was employed to obtain them. The implication of this assertion is the risk of over-estimation of FoS in remedial designs, an undesired consequence.

In most real life situations, the final state of the collapsed slope usually comprises the aggregation of a number of retrogressive failures and each stage of failure will have a different pore water pressure regime associated with it. This makes it close to impossible to establish the representative slope geometry and pore water pressure regime to be used in the back-analysis for any stage.

4.0 CONCLUSION

The commonly employed LEM of stability analysis, being a lower bound solution, leads to overly-optimistic evaluated shear strength parameters when used in the back-analysis of earthworks failures.

Back-analysis of earthworks structural failures cannot generally claim validity as a procedure to obtain geotechnical engineering parameters for subsequent engineering design work to supplant laboratory tests on soil specimens carried out under appropriate testing parameters.

The use of shear strengths derived from the back-analysis of a failed slope may lead to the design of remedial works appearing more generous than they may really be. ■

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