m). The segment lengths, large angular range of the joints (+/- 45 degrees or more), and small casing (27 mm inside diameter) allow the system to tolerate very large movements and remain in service (Dasenbrock, 2010).

Stability, repeatability, and accuracy have been assessed for vertical and horizontal SAAs. Duzuke et al. (2010) mounted SAAs horizontally in a 10 m long test specimen built as a steel-reinforced bridge deck. It was deformed with hydraulic jacks and deformations were measured by SAAs and linear variable differential transformer (LVDT) sensors. Accuracy and repeatability were approximately 0.6 mm. Rollins et al. (2009) measured the lateral deformations of piles fitted with SAAs and traversing inclinometers and found the measurements agreed to better than 2 mm over the 13 m vertical span of the test. The discrepancy was thought to be due, at least in part, to the fixation of the SAA within the pile. However, the agreement is within the accuracy to be expected from comparing two tilt-based instruments, one of them traversing during the short time between deformation stages. In other tests (Danisch, 2010), four SAAs 68 – 70 m in length were mounted in boreholes that also contained standard traversing inclinometer casing. In a test extending over 5 months and involving man-made deformations of the slope of up to 70 mm, the manual and SAA measurements agreed to within 2 mm. Long-term stability of 32 SAAs, in operation for up to three years, has been shown to be 1.5 mm at 32 m, and to vary with length as approximately the square root of length (Danisch, 2010). In addition, repeatability and accuracy have been found to be in the 0.6 – 2 mm range in several studies (Rollins et al., 2009; Duzuke et al., 2010; Danisch, 2010). More detailed information on the design of the SAA is available in Abdoun et al. (2007), Bennett et al. (2009) and Measurand (2010).

Comparing SAA performance to Reference Sensors

Figure 2 shows comparative deformation data, and example vibration data taken in laboratory tests during a full-scale lateral spreading experiment conducted at the University of Buffalo. The earthquake engineering simulation laminar box at the University of Buffalo facility is 5 m long, 2.75 m wide, and 6 m high and is capable of containing 150 tons of sand. After this laminar container was instrumented and filled with loose sand and water, two 100-ton hydraulic actuators were used to input predetermined motion with a 2 Hz frequency to the base of the box. The resultant soil liquefaction and lateral spreading was monitored using accelerometers within the soil deposit and on the ring laminates, potentiometers (displacement transducers) on the laminates, pore pressure transducers and two SAAs within the soil deposit. Each of the SAAs was 7 m (23.0 ft) long and contained 24 3D sensing elements. The acceleration and lateral displacement data from the SAA compared to the ring accelerometer and potentiometer data, respectively, are presented in Figure 2. This data was collected during a sloping ground test, where the base of the box was inclined 2^{o}. For more information on this full-scale experiment see Dobry et al. (2010).

One of the Mn/DOT sites has companion instrumentation in the form of manual inclinometers adjacent to SAA installations. Data from this site showed the SAA measurements to be in good agreement with the existing inclinometer data (see

Figure 3). Observed benefits of the SAAs have included web-based monitoring, the ability to tolerate (and observe) very large deformations, and fewer operational problems (related to weather or operator error) as compared to other in-situ deflection monitoring sensor systems (Dasenbrock, 2010).

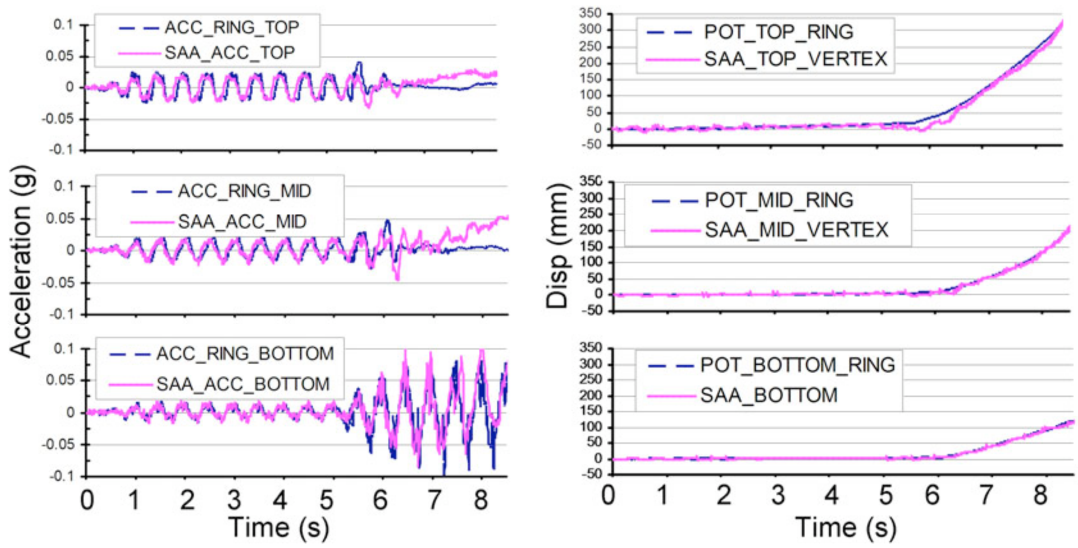

Figure 2. Lateral acceleration (g) and displacement (mm) from one SAA system compared with accelerometers and potentiometers on the laminar rings near the top of the soil deposit, at the middle, and at the base of the laminar container.

APPLICATIONS OF REMOTELY MONITORED SAA SYSTEMS

Landslide Monitoring in Crookston, MN

At two sites in Crookston, MN, the Red Lake River was causing erosion at the base of slopes adjacent to US Highway 2. A major landslide occurred at the west site in downtown Crookston in 2003. Manually read instrumentation was installed shortly after the 2003 event; three SAA sensors were installed in 2007 as part of a pilot study to compare the data quality and effectiveness of the SAA equipment compared to traditional systems for SHM applications. The data appeared of similar quality with the added advantages that: 1) data was acquired far more frequently, resulting in the greatly improved ability to judge rate effects; 2) data could be viewed remotely, significantly reducing travel and field time; 3) the array was more flexible allowing very large displacements to be recorded; and 4) automated data collection allowed data acquisition regardless of weather or flood conditions. A plot of traditional manual traversing-probe inclinometer data compared to the SAA data from sister installations at the downtown Crookston site (installation #2) is shown in Figure 3. More than 0.77 m of slow creep has been observed over three years. At the second site, east of the city, a set of two SAA systems was installed on a slope three months prior to a catastrophic failure, which destroyed part of a divided highway.

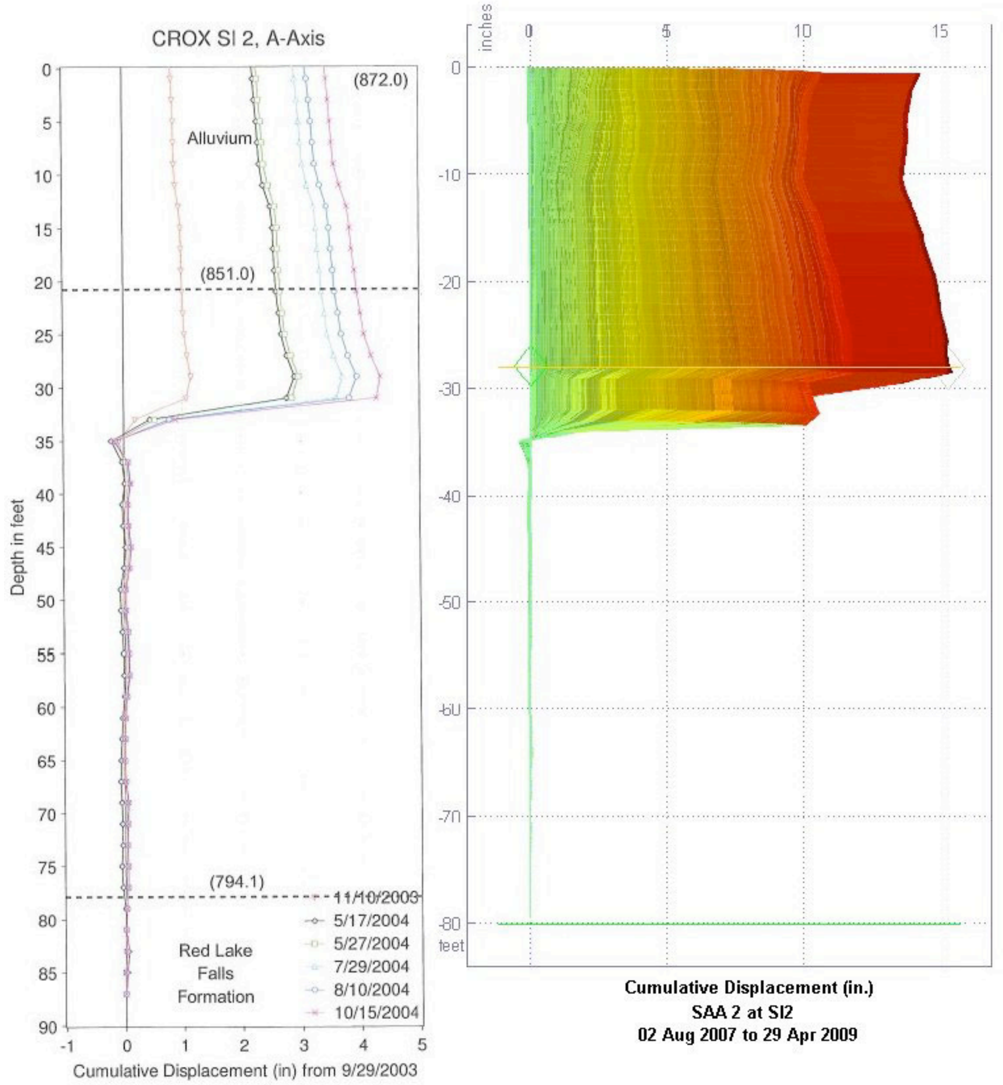

Figure 3. Traditional traversing probe inclinometer data (left) compared to SAA data (acquired at 4 hr-12 hr intervals) at Crookston West installation #2 (right).

At the eastern Crookston site, the SHM program provided clear SHM data that the slope was actively failing: key information for the decision to close WB US 2 and re-route traffic a week in advance of a major landslide that destroyed over 600 feet of highway. The SAAs captured a large number of interesting details about the failure geometry and rates. A comprehensive discussion of the landslide monitoring at the Crookston sites is given by Dasenbrock (2010).

Embankment Stability Monitoring in St. Paul, MN

As part of the I-35E reconstruction at the junction with I-694, an embankment was widened and a small additional amount of fill was placed on the west side slope. Distress was soon observed in the shoulder paving; after several 'patches' it continues to be a nuisance problem. Three SAA systems are now operational at the site and are providing quality SHM information on the rate and magnitude of the ongoing movement. Not seen at other sites, some unusual "wobbly" strain data suggests that the embankment may be settling and causing some buckling in the SAA systems. As there are compressible clay layers underlying the embankment and weak organic materials near the toe, the observed behavior seems reasonable. Here, as at the other sites, the engineering analysis is greatly enhanced by the large amount of time-domain data, which is acquired twice daily at this site. A site profile is shown in Figure 4; a SAA is installed at each boring location.

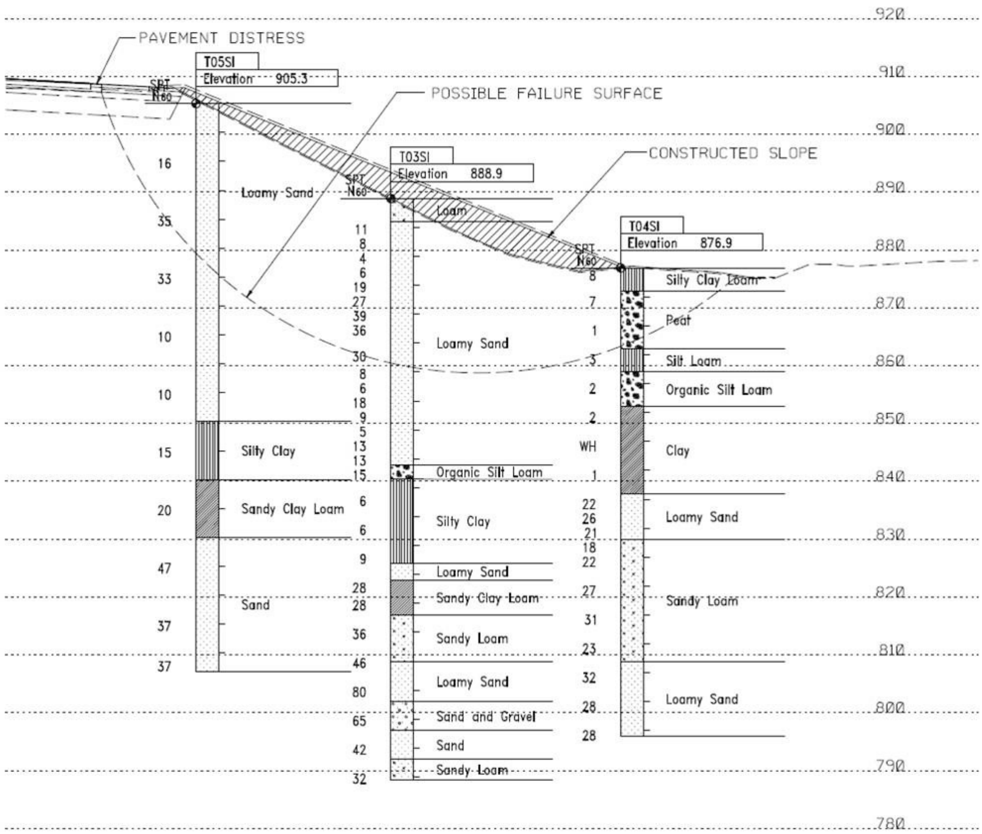

Figure 4. Three SAAs were installed after distress was repeatedly observed.

Construction Slope Stability Monitoring in Minneapolis, MN

On January 31, 2009 a temporary slope on a construction project in downtown Minneapolis failed, likely influenced by an adjacent excavation. There was an immediate need to monitor the stability of the slope frequently and reliably following the initial failure. Even though the site was close to Mn/DOT offices, a SAA with web-monitoring was used to provide regular and frequent reading intervals, and have the information available (from many locations) in near-real time. SAA data clearly indicated when contractor excavation and backfilling activities were occurring and showed that no additional significant impacts resulted from the revised construction process. Data showed that after the construction activities in the immediate area were concluded the slope had been stabilized.

Bridge Approach Embankment Monitoring on US Route 169 in Osseo, MN

Two arrays were placed below a future bridge abutment embankment, to monitor vertical deformation near a pile group where downdrag (due to underlying compressible soils) was expected. Over 13 months, 100 mm of deflection at the center of the embankment fill, tapering to 0 mm outside the wall at the side of the abutment have been observed. Figure 5 shows a plot of the displacements across the 29 m (96 ft) of one array and the rate of the displacement for the segment where the largest deformations were observed (at 28.3 m (93 ft) along the array, near the free end). The data is being used in conjunction with strain gage data from two instrumented piles; to examine the effects of consolidation settlement below the approach embankment fill on pile loads. The time-domain data correlates exceptionally well with the field notes about the construction activities at the site. This is the first Mn/DOT project where the SAAs were installed prior to any deformation or distress occurring; each of the slope sites had pre-existing distress.

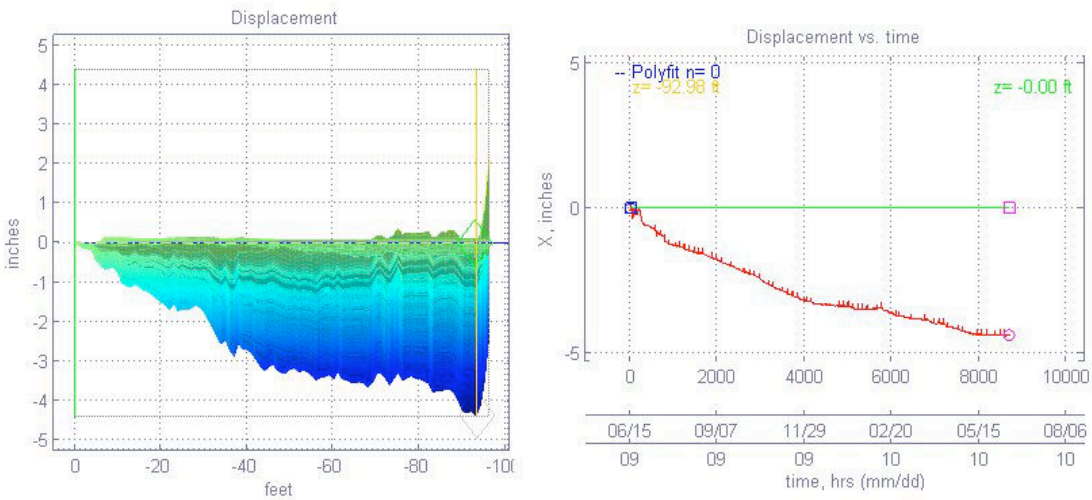

Figure 5. Horizontal SAA showing up to 100 mm of deflection (left). Deflection rate of a single element 28.3 m (93 ft) along the array (right).

GEOTECHNICAL SYSTEM HEALTH-ASSESSMENT WITH REMOTE SENSING MEASUREMENTS

Health-assessment and performance prediction of geosystems are difficult tasks due to the complex and random nature of geomaterials. Most of the current assessments of disturbed systems depend on annual or bi-annual visual inspections of assets, which reveal very little about the internal condition and future performance. Similar to the recent success in SHM for 'structures', the reliability and safety of geosystems can also be achieved with efficient programs that continuously monitor, assess the health, and adaptively manage these systems. Although each application has a slightly different character, automated monitoring is playing a key role in the geotechnical SHM at seven Mn/DOT sites, providing near-real-time observations and a significantly greater density of time-domain data than would be practical or economical with manual methods. Geotechnical SHM, as described in the SAA case studies above, is part of a proposed framework for comprehensive multi-scale monitoring and analysis for health-assessment of distributed geotechnical systems, such as reinforced fills, highways over abandoned mine works, levees and flood-control infrastructure, see Figure 6. In the near future, advances in technology will allow for remote ground based light detection and ranging (LIDAR) and satellite based interferometric synthetic aperture radar (InSAR), to be used more commonly, in conjunction with web-enabled earth stations, to monitor whole systems of distributed local sensors installed on distributed infrastructure in near-real time.

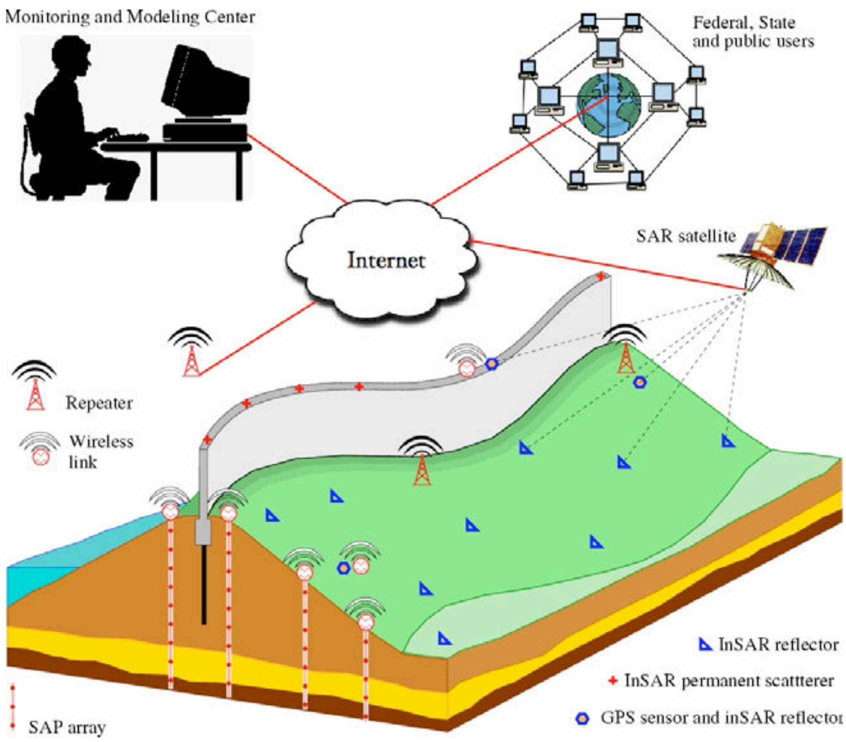

Figure 6. Schematic illustration of the multi-scale monitoring of flood-control levees: InSAR reflectors, SAAs for local monitoring, and GPS sensors.

Topographical, hydrologic, and other information, in combination with geotechnical behavior or failure models, which are refined based on sensor data, can be used to identify critical and degrading structural or geotechnical assets with a higher probabilities of failure to assign risk and priority. Infrastructure elements with greater likelihood of failure, or significant failure impacts, can then be instrumented with additional sensors, remediated, replaced, or taken out of service proactively, saving money and protecting the public. Advances in in-situ sensing and electronic communication (such as mobile broadband and cellular modems), in both terms of quality and lower cost, are making this potential a reality even on 'typical' projects.

CONCLUSION

Real-time structural health monitoring (SHM) of geotechnical assets, has proved to be valuable on several diverse Mn/DOT projects. SAA systems, in addition to other automated sensors, are well suited to collecting and recording information during construction and after facilities are in service and can be used to monitor geotechnical infrastructure as part of a comprehensive quality control / quality assurance program or on a case specific basis, such as high risk projects. While the spatial density of SAA readings is similar to that of manual traversing inclinometer probes, frequent automated readings can provide useful insight into external factors that promote instability and the rates and magnitudes of the resulting movements. The ability to collect large amounts of time-domain data has proved to be a significant strength of ShapeAccelArray (SAA) systems, in addition to their tolerance of large deformations and continued operation during harsh weather and extreme events. SAAs appear to be a very useful geotechnical SHM tool. "Structural" health monitoring has been a recent and achievable goal of owners and organizations, such as the Federal Highway Administration. SHM can and should now be extended to similar health-assessment of geotechnical assets through real-time monitoring-perhaps a new term, "geotechnical health monitoring" (GHM) is in order?

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Combined Seepage and Slope Stability Analysis of Rapid Drawdown Scenarios for Levee Design

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ABSTRACT

The strength of levees can be affected during fluctuations in the water table. It is also possible for the climate to have an influence on the position of the water table in an earth levee. Traditional methods have resulted in approximate methods for dealing with the transient fluctuations of the water table in a levee. These approximations are generally accepted in engineering practice but the question can be rightfully raised as to how these approximations compare to a rigorous transient combined seepage and slope stability analysis. Software technology has significantly changed in recent years and is now at the point where it is much easier to perform transient seepage analyses. There are new questions that can be asked. Does an effective stress analysis diverge significantly from the 3-stage Duncan (1990) analysis? If so, under what conditions?

This paper compares the Duncan (1990) three-stage methodology for analyzing rapid drawdown scenarios to a combined transient seepage and slope stability analysis. Traditional limit equilibrium methods will be utilized in the slope stability analysis and the accommodation of saturated and unsaturated pore-water pressures will be considered. Analyses of a number of typical cross-sections will be considered in order to determine the potential influence of geometry. The intent of the paper is to illustrate scenarios under which the Duncan (loc. cit.) methodology produces similar results to the results of a more rigorous analysis.

INTRODUCTION

The rapid draw-down scenario is one of the most severe loading conditions which can afflict a levee. Rapid draw-down consists of a relatively high water table which has remained against an earth levee for a period of time such that pseudo steady-state conditions are created in the levee. The high water table would be consistent with high water levels during a flooding season. Often such floodwaters can disappear within a relatively short period of time thus creating a rapid draw-down scenario on the levees. In such scenarios, the pore-water pressures present in the levee during the flooding do not have enough time to dissipate. This is particularly true for clay-type materials where the hydraulic conductivity of the material is relatively low. A situation is therefore created in which heightened pore-water pressures on the up-stream side of a levee can trigger either deep or shallow failures.

Such rapid draw-down scenarios can be analyzed by either a i) total stress or ii) an effective stress analysis. Traditionally, the total stress analysis has been utilized as it is easier to implement in practice. However, the fundamentals of the interplay between effective stresses and pore-water pressures are not represented in a total stress analysis. Therefore, the limitation associated with a total stress analysis is related to the fundamental behavior of soil as failure conditions are approached. The total stress analysis may lead to a more conservative design which may result in considerably higher construction costs. This paper explores a comparison between the total stress and effective stress methodologies for typical material types. The potential differences between the two methodologies for deep and shallow slides are examined and the opportunity to optimize designs using an effective stress analysis is examined.

BACKGROUND

The USACE (2003) slope stability engineering design manual divides earth embankments and levees into two categories:

1. Free draining soils
2. Low permeability soils

In the case of free draining soils the design procedure that is recommended is an effective stress analysis where the initial and final pore-water pressure levels are determined from a steady-state analysis where the initial and final conditions of the water table are determined using two separate steady-state seepage analysis.

For low permeability soils, the design manual recommends a three-stage approach which uses a combination of effective strength results and consolidated-undrained (total) strength results to estimate a worst-case scenario that represents a conservative design. The three-stage approach represents a methodology based partly on a total stress analysis as a limiting condition.

The three-stage procedure has evolved from first version called the Lowe and Karafiath (1959) method and later to the USACE (1970) method. Duncan et al. (1990) reviewed both of these methods and suggested an alternative three-stage analysis procedure.

The Duncan et al (1990) total stress approach provides an easy methodology for the analysis of rapid draw-down conditions in an earth dam or levee structure. However, it is subject to the following limitations:

1. The time over which rapid drawdown occurs is not accounted for in the procedure,
2. The method assumes that a consolidated-undrained laboratory test represents the limiting condition along the entire critical slip surface. A single value of undrained shear strength is not appropriate along the entire slip surface (Kerkes, et al., 2003),
3. The determination of an appropriate value for the undrained shear strength value for the analysis can be complicated (Kerkes, et al., 2003),
4. The location of the critical slip surface is assumed to be deep and to not change location during the rapid drawdown sequence.

Given that the Duncan et al. (1990) total stress approach is applied to the engineering design of earth levees it would seem important to more clearly understand the performance of the empirical total stress methodology under differing material conditions. It is worthy of note that the Duncan et al. (loc. cit.) approach was conceived and designed in a time when a geotechnical engineers did not have access to software tools required in order to perform a transient saturated/unsaturated seepage analysis.

METHODOLOGY

The methodology used for the present analysis is to perform a series of analysis which perform a rapid draw-down analysis using both the Duncan et al. (1990) 3-stage approach and an effective stress approach. In order to first prove the correctness of the implementation of the Duncan et al. (1990) method a few benchmarks are first presented. The comparison will then proceed to compare the more complex examples originally presented by Duncan. So the general steps are as follows:

1. Benchmark the Duncan method,
2. Pilarcitos comparison,
3. Walter Bouldin comparison.

It should be noted that there are a significant number of input variables which can influence the outcome of the analysis. Some of the variables include:

- Slip surface location (deep / shallow)
- Stress state approach (effective stress / total stress)
- Saturated / unsaturated shear strength conditions
- Variance in seepage or stress - deformation material properties
- Variance in the slope angle
- Variance in material heterogeneity
- Variations in slope stability calculation methodology (i.e., Spencer, Morgenstern-Price, GLE, etc.)

For the sake of simplicity, the present analysis will focus on: i) comparison between effective and total stress approaches, and ii) variances in material properties.

The SVSLOPE® / SVFLUX™ software (SoilVision Systems Ltd., 2010) are used for the analyses of both the 3-stage methodology and the effective stress combined seepage / slope stability analysis. The effective stress analysis methodology involves two primary steps. First the rapid drawdown scenario is solved in a seepage model using appropriate draw-down boundary conditions. The pore-water pressures are started from steady-state conditions with the reservoir at the maximum elevation. Pore-water conditions are saved at regular intervals. The pore-water pressures are then input into a slope stability analysis and the factor of safety is computed at each saved time-step. The pore-water pressures as well as the external load resulting from the reservoir at its current level are considered in the analysis.

Unsaturated soil conditions are present above the water table in a levee analysis but will not be considered in this comparison. Unsaturated shear strength properties will have the effect of raising the calculated factors of safety.