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ABSTRACT

At UNC Charlotte, the authors have used a retaining wall failure case history to cover the different modes of failure of retaining wall and to highlight the importance of global stability failure. Specifically, this case study has been used by the authors in undergraduate and graduate courses of geotechnical engineering to highlight the importance to include in the design process the assessment of global stability. The project is valuable to students due to wealth of data including field and laboratory site investigation, monitoring data from slope inclinometers, amongst other data. The students are presented with the initial design information including wall height, backfill information, geosynthetic reinforcement type and layout, etc. The first assignment requires students to check conventional internal and external stability. Then the students are presented with post failure photos of the wall. The failure incident is discussed in detail and the students are then asked to take a second closer look of the project information to try to explain the failure. This time around they also have access to the post failure inclinometer data and field reports that included evidence of surface cracks on the pavement built on the top of the wall. With this available information students successfully explain the failure mode via global slope stability analyses.

INTRODUCTION

In the US, undergraduate curriculums for BS in civil engineering often only require 1 or 2 core courses in geotechnical engineering. This often translates into a challenge to have to cover considerable material in limited number of lecture hours. For the topic of retaining walls design and analysis instructors often have to cover the basics of lateral earth pressures and then jump to design aspects such as typical retaining wall modes of failure such as sliding, overturning, bearing capacity, and global stability. Global stability in many instances is mentioned but detailed coverage moved to the section of slope stability if time permits. At UNC Charlotte, the authors have used a retaining wall failure case history to cover the different modes of failure of retaining wall and to highlight the importance of global stability failure. Specifically, this case study has been used by the authors in undergraduate and graduate courses of geotechnical engineering to highlight the importance to include in the design process the assessment of global stability. The project is valuable to students due to wealth of data including field and laboratory site investigation, monitoring data from slope inclinometers, amongst other data. The students are presented with the initial design information including wall height, backfill information, geosynthetic reinforcement type and layout, etc. The first assignment requires students to check conventional internal and external stability. Based on the results from this first assignment students discuss the appropriateness of the design via informal in class discussion and debate. Then the students are presented with post failure photos of the wall. The failure incident is discussed in detail and the students are then asked to take a second closer look of the project information to try to explain the failure. This time around they also have access to the post failure inclinometer data and field reports that included evidence of surface cracks on the pavement built on the top of the wall. With this available information students successfully explain the failure mode via global slope stability analyses. The case history is concluded with discussion of the successful remediation scheme followed by the consultant and client.

This case history has been found to be a powerful tool for emphasizing the importance to consider all possible modes of failures in geotechnical design, and to keep in mind the importance of always checking global stability of a retaining structure.

FAILURE CASE HISTORIES AND FORENSIC IN GEOTECHNICAL ENGINEERING EDUCATION

The use of geotechnical failure case histories in geotechnical engineering has long been recognized to be a valuable education tool (e.g., Bosela, 1993; Rendon-Herrero, 1993; Delatte, 1997). These authors have pointed out the benefits of integrating the lessons learned from failure case histories into civil engineering lessons. The study of such failure case studies helps the students grasp the often abstract analytical and design procedures taught in their coursework with real world projects. The impact and effectiveness is even greater when the case history involves a failure case history as it reminds the student the technical, ethical, and professional issues and responsibility faced by professional civil engineers in the real world. A more recent approach has been to integrate forensic engineering and failure case histories in the civil engineering curriculum (Delatte and Rens, 2002; Janardhanam, 2010). This has been done traditionally by either offering of a stand-alone forensic engineering course as a technical elective, or by incorporating failure case histories in different courses within the civil engineering curriculum. At UNC Charlotte, the institution of the authors, has use both approaches to incorporate forensics and failure case histories into the civil engineering curriculum. However the focus of this paper is on the latter approach, specifically we describe how through incorporation of a few lectures on a simple case study of a mechanically stabilized earth (MSE) wall failure was an effective way to reinforce basic but important geotechnical engineering concepts and design principles as well as a way to introduce senior undergraduate students to forensic engineering and principles of failure analyses. The paper will primarily share the developed MSE wall failure case study including the approach used to present it. As pointed out by Delatte (2000) one main obstacle for faculty to incorporate failure case studies into existing courses is the time required to research and prepare lectures on the case study. This paper hopes to offer material on the specific topic of global stability of MSE walls. Interested faculty are welcome to contact the first author to request detailed material on this case history beyond what is presented in this paper.

BACKGROUND ON LECTURE COVERAGE PRIOR TO CASE HISTORY PRESENTATION

At the undergraduate level, UNC Charlotte civil engineering students first take an introductory course on geotechnical engineering (Geotechnical Engineering I). This course prepares students on soil mechanics including topics such as soil origin and definitions, soil types and classification, site investigation techniques, effective stress principle, stresses in soil masses, Mohr circle, seepage, etc. This general course on soil mechanics is usually taken at the junior level and is offered in parallel with a soil mechanics laboratory course. The second required course on geotechnical engineering (Geotechnical Engineering II) involves applied geotechnical engineering to cover analysis and design of shallow and deep foundations, retaining structures, excavations, and slope stability. It is in the context of this second course that the authors have implemented the MSE wall failure case history which is described in the following section.

THE MSE WALL CASE HISTORY

As mentioned earlier, the students in Geotechnical Engineering II at UNC Charlotte are presented with MSE wall failure case history in a gradual way. This is done at a stage in the semester right after completion of classical lateral earth pressure theories and review of design of retaining structures including the requirement to check for different failure modes such as sliding, overturning, bearing capacity, and global stability. At this point students have completed one or two assignments involving classical problems of design of gravity and cantilever retaining walls. The first lecture where we present the case history involves presentation of MSE wall design and review of internal and external stability of MSE walls including reference to design manuals (e.g., FHWA manuals: FHWA, 2010). Then as mode of a class group project, we present a general description of the MSE wall project. At this point students are not told that the MSW wall has failed, but rather presented with the project information, proposed wall geometry, and detailed geotechnical information. This first lecture also includes presentation of the actual MSE wall design used. This is found to be useful as the focus of the course is not on MSE wall design, but rather overall design and analysis principles of retaining structures. After this initial lecture, students are given their first group assignment. They are asked to compute and check the minimum factors of safety of this wall for the different anticipated modes of failures. The statement of the problem is chosen such that students have to revisit the different modes of failures discussed in previous lectures and in the course textbook. After one week students present their assignment with a summary table of the computed minimum factor of safety. Over the years the experience of the first author is that the majority of the students are successful in obtaining minimum factors of safety for sliding, overturning, and bearing capacity. However, the global stability is typically not included because of time constraints, perceived complexity, limited access or familiarity to limit equilibrium software, etc. It should be pointed out that in geotechnical engineering II students are exposed to student version of slope stability software such as Slope/W (Geo-studio, 2012) and Slide (Rocscience, 2012). We also provide the students with a simple Excel spreadsheet for wedge type stability analyses which could also be used to do cursory or preliminary assessments of the global stability of a retaining wall.

The second lecture presented to the students is given the lecture after they submit their first project assignment. In this second lecture we present a summary compilation of the factors of safety presented by the different groups. In this presentations we show summary plots (results are presented without revealing identity of the names of students) of the results presented by the class. This allows discussion of variability of results associated with differences in selected geotechnical parameters, critical failure surfaces, etc. If any groups present global stability results we present those to the class and highlight to all that this mode of failure is a very important design consideration that must always be checked. If no group presents this case, then we proceed with the presentation of the actual MSE failure case history. The presentation of photos of cracks, inclinometer data at different times after construction completion, are found to be extremely effective to highlight the importance of this mode of failure. Usually the class comes to a complete silence when they see that the MSE wall that for the most part they thought was adequate design actually failed. After presentation of failure photos and data, we present the instructor's set of analyses of the same MSE wall. We provide handouts summarizing our set of analyses which like theirs will include factors of safety for sliding, overturning, bearing capacity, and settlement, but most importantly for this case history global stability. The global stability analyses are presented using specialized software like Slope/W or Slide, but we also show how even a simplified approach such as the Excel wedge analysis can identify issues of global stability for this case history.

The second assignment provided to the students is to revisit their calculations this time with special focus on global stability. We also request evaluation of an option of use of a toe berm for stabilization of the failing MSE wall. Students are given 1 week to complete this second assignment. Upon receipt of the second assignment the instructors provide a brief presentation of the repaired MSE wall together with monitoring data showing that the repaired MSE wall is performing satisfactorily for more than 5 years. This is often complemented with a project site visit since the site of this case history is less than 30 minutes driving from the UNC Charlotte main campus.

CASE HISTORY DETAILS

General Information presented for first assignment

The subject MSE wall is a segmental retaining wall about 580 feet long and an average change of grade height of about 18 feet. The wall foundation is about 3.5 feet below ground surface and the geogrid reinforced block had a width between 13.5 to 16.5 feet wide. Vertical spacing of the geogrid varied with elevation and ranged from 8 to 16 inches. Since internal failure was not reported, and given the undergraduate level of the course used to introduce this case history, evaluation of the internal stability of the MSE wall is not included as part of this case history project.

A profile showing the wall geometry is shown schematically in Figure 1. This figure shows the top of the MSE wall being a large asphalt paved parking area. Students are presented with a set of 14 geotechnical boring logs which include standard geotechnical information such as soil descriptions, Standard Penetration Test (SPT) data, moisture content data with depth from select samples, and gradation and Atterberg limits for select samples. Groundwater information is also provided in the borehole logs where some included piezometer standpipe installations.

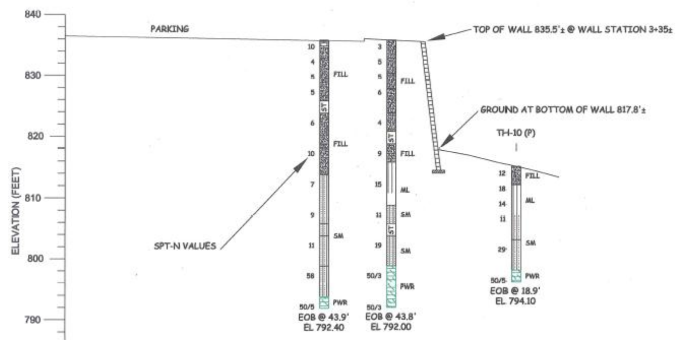

Fig. 1. Representative Cross section of the MSE wall.

The generalized soil profile for the foundation soils of this MSE wall consisted of 15 to 20 feet of residual soils underlained by partially weathered rock. The foundation residual soil layer was reported as mainly being a stiff, low plastic sandy silt (ML) to a medium dense to dense silty sand (SM). However some boreholes indicated presence of medium stiff low plastic clay (CL) and high plastic silt (MH). The presence of these weaker soils was confirmed to be close to the section of the MSE wall that failed. Students are presented with a site plan showing the location of the boring logs and are asked to prepare generalized soil profiles along different sections of the MSE wall. This is also considered a valuable component of this case history as it forces students to deal with site variability and the need to do interpretation and generalizations to allow for geotechnical design.

The MSE wall backfill was primarily a compacted sandy silt, of low plasticity. This backfill material was also included in the geotechnical borehole logs with SPT blow count values typically indicative of a firm to medium stiff consistency. Students are requested to review borehole information and associated laboratory data to assign geotechnical parameters and properties.

This case history also included laboratory test, results such as consolidation and consolidated undrained (CU) triaxial compression tests, carried out on Shelby tubes samples retrieved from both the MSE backfill and the residual soil foundation layer.

Failure Information presented after first assignment

Upon completion of the first assignment, and review and compilation of answers by course instructors, the students are presented with a set of photos and field data that shows how the propose MSE wall failed. Due to litigation reasons photos are not presented in this manuscript, but students get to see a PowerPoint presentation of the failure of a portion of this MSE wall. The MSE wall construction was completed and a month later the parking lot was paved about 1 month later. About 6 weeks after the parking lot was completed, cracks were observed in several sections of the parking lot. Cracks were observed along a section of the MSE wall of about 50 feet length. Cracks were located about 20 feet behind the top edge of the wall (i.e., beyond the reported length of the geogrid stabilized earth section) and were oriented parallel to the wall alignment. Cracks appeared at the beginning of the rainy season. The cracks were initially fairly narrow (less than an half an inch wide) but in a matter of 4 weeks they quickly enlarged to 1 to 2 inches width and 2 to 3 inches depth. The geotechnical monitoring included installation of several slope inclinometers, crack meters, etc. Students are presented with data of crack deformation and slope inclinometer data as function of time for a period of about 5 months. After which the wall failure was repaired with a toe berm. During this second presentation, students also receive rainfall data for the corresponding monitoring time period. The students are then presented with slope stability analyses showing that global stability was the failure mechanism in the portion of the MSE wall where CL and MH residual soils were present (See Figure 2). At this point, students are requested to carryout global stability analyses in light of this new evidence including slope inclinometer data. Students are also requested to design a simple toe berm as a remediation measure for the portion of the MSE wall that failed.

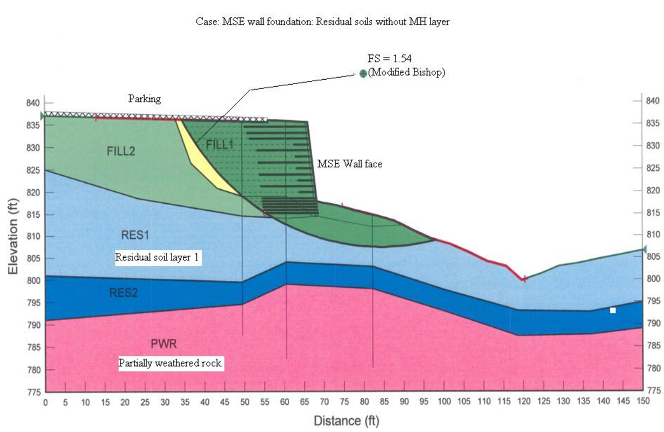

Fig. 2. Example output from Slope/W Model for Global Stability Analyses of MSE wall

Third assignment and site visit

The third and final lecture for this case history includes review of the proposed stabilization toe berms and a site visit to the repaired MSE wall. The wall has been performing satisfactorily now for over 4 years. Students get to see the actual wall and walk near the area that failed and that has been repaired.

SUMMARY AND CONCLUSIONS

The feedback from students about the presentation of a failure case study followed by discussions in the classroom on the importance of stability checks is very positive. Students also expressed wanting to see more such case histories of failure of geostructures, forensic investigation demonstration and remediation measures presented in all their geotechnical engineering design courses. There is a human psychology component that enhances the learning of students when they actually see the failure of a structure and tie this to the relevant technical content. The resulting better understanding of the subject matter translates into a better "learning outcome".

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