The May 25th 2011 Railroad Embankment Failure in Ann Arbor, Michigan, As a Means for Teaching Geotechnical Engineering

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ABSTRACT: *A 30-m long railroad embankment failure that occurred on May 25 2011 in the city of Ann Arbor, Michigan, is presented. Emphasis is given on the field observations of the failure, the characterization of the site conditions and the seepage and slope stability analyses, all of which represent important components of the training and practice of a geotechnical engineer. The failure occurred following a record wet season that resulted in ponding water against the embankment and high enough water pressures and exit gradients that resulted in instability of the railroad embankment. Detailed background material and the methodology for using the case history in geotechnical engineering education are presented.*

KEYWORDS: education, embankment, stability, seepage, railroad, site characterization

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

The case history of a railroad embankment failure, shown in Fig. 1, that took place in Ann Arbor, Michigan, on the 25th of May 2011 is presented as a means for teaching fundamental principles of geotechnical engineering. An advantage of this case history as an education tool is that it can be taught at different levels and give the instructor the opportunity to emphasize several different topics in soil mechanics and geotechnical engineering. Additional advantages include the impressive nature of the failure, the detailed characterization using in-situ and laboratory approaches, and the wealth of lessons learned that can be readily understood by students.

The role of case histories in formal and informal geotechnical education has been recognized for many years (e.g., Peck 2014, Rogers et al. 2008). Case histories provide the unique opportunity to learn from someone else's successes or failures, to empirically assess what worked and what did not, and for students to understand that theory is important and has significant implications in engineering practice. More recently, Pantazidou and Orr (2012) listed ten key learning outcomes achievable by geotechnical engineering courses. This contribution aims to document a case history that includes eight of these key outcomes.

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DESCRIPTION

Location

The failure site is located to the north of downtown Ann Arbor in Michigan, USA, as shown in Fig. 2b. The failure took place on the railroad embankment that is heading parallel to Plymouth Rd and adjacent to residential structures. Fig. 3 illustrates an intact portion of the embankment immediately to the East from the failure location. The failure resulted in:

(a) Shutdown of the railroad for an extended period of time;

(b) Closure of Plymouth Rd for two days; and

(c) Flooding and debris deposition on the downslope side of the embankment that damaged a public park southwest of Plymouth Rd and deposited additional sediments in a natural stream, as shown in Fig. 4.

The failure took place in the evening of the 25th of May 2011, at 9:23 pm, during a significant rainfall event. No trains were operational during that time. In the 24 hrs. preceding the failure, the weather station at the University of Michigan, located about 2 km from the failure location, recorded rainfall precipitation of 88.4 mm (3.48 inches) which is the sixth highest since 1906 when the weather station started recording data. The total precipitation from March 2011 to May 2011 was equal to 423.2 mm (16.66 inches), which is the highest on record, with the second highest of 421.9 mm (16.61 inches) recorded in 1946.

Figure 1. View of the railroad embankment failure looking East.

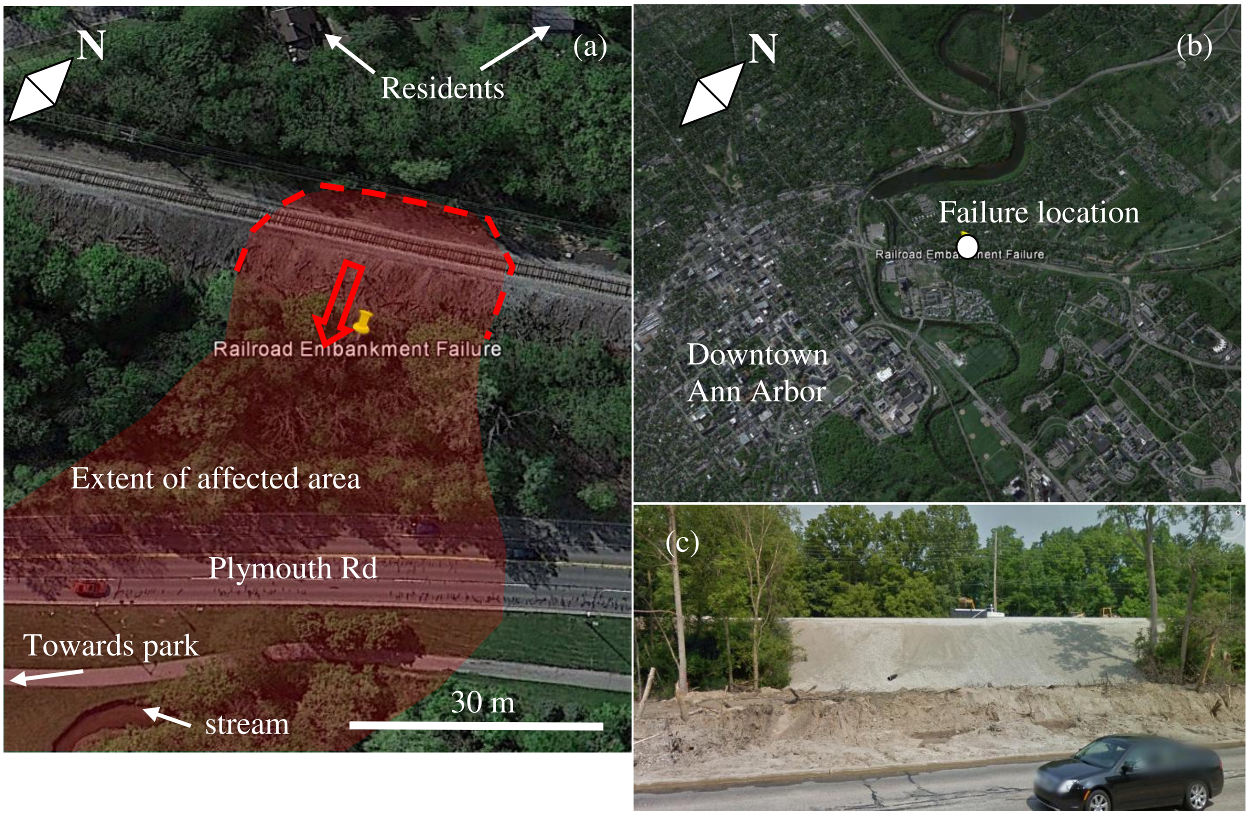


Figure 2. (a) Satellite imagery of the railroad embankment at the failure location; (b) location of the failure; (c) View of the repair works as recorded by coincidence by the Google Earth Camera.

Figure 3. View of intact portion of the embankment immediately to the East of the failure area. One can see that the uphill part of the embankment (left) is supported by natural ground that is at a much higher elevation than the downhill part of the embankment (right).

Figure 4. View of the conditions downhill of the failure showing deposition of debris and water. Trucks and dozer are operating on Plymouth Rd. and flooded area further back is a flooded public park.

Description of Activities

The authors visited the site approximately 12 hrs after the failure, in the morning of the 26th of May 2011, while the repair crews were clearing Plymouth Rd (shown in Fig. 4), and before any embankment repair intervention. This allowed in-situ observations of the geomorphic and hydrogeologic characteristics of the site, the survey of the geometry of the intact embankment adjacent to the failure, the investigation of the exposed failure surface, the collection of photos and videos of the site as well as disturbed sampling of bulk material along the failure plane on the stable part of the embankment for laboratory characterization of the soils involved. Material was sampled using a shovel and was placed in four 5-gallon buckets. In addition, in-situ shear wave velocity measurements were conducted. The collection of this data was valuable in providing a comprehensive understanding of the failure conditions.

Description of the Embankment and Site Conditions

The embankment is constructed partially on a naturally sloping ground and has a total height of 7.6 m as shown in Fig. 5. Its crest, that supports the railroad lines, has a width of 9.3 m. The embankment fill consists of two layers. The main layer (Fill Soil 1) is a silty sand (SM). A surficial layer of very small thickness is also present and consists of coal ash residuals (Soil 2). The natural soil that underlays the embankment is a sandy clay of low plasticity (CL) that geologically is described as very dense glacial deposits (Native Soil-Soil 3).

During the site visit, it was observed that the failure location was at a local natural depression that was receiving and accumulating surface water from a wider area. After careful inspection, the authors hypothesized the existence of seasonal ponding water. The surface soil on the uphill side of the embankment was very wet with vegetation that is typical of marshes, such as reeds. Next to the embankment where the water appeared to nearly permanently ponding and below trees there was no vegetation (see web-based supporting information titled "Photos and "Videos"). These conditions were found to be unique compared to other locations along the axis of the embankment. In addition, the level of water could be clearly seen as a watermark on the trunks of trees, as shown in Fig. 6. Based on these observations it was evaluated that the depth of the ponding water could have reached up to 120 cm. Local residents confirmed the existence of ponding water adjacent to the embankment. In fact, it appears that a neighbor used to feed visiting ducks at that location. Retention of ponding water was not part of the original embankment design. It is important to note that ponding water existed for at least some period of time prior to failure. However, the spring of 2011 was particularly wet and probably more water accumulated compared to previous years. It is also not entirely clear whether a clogged storm drain existed in that location.

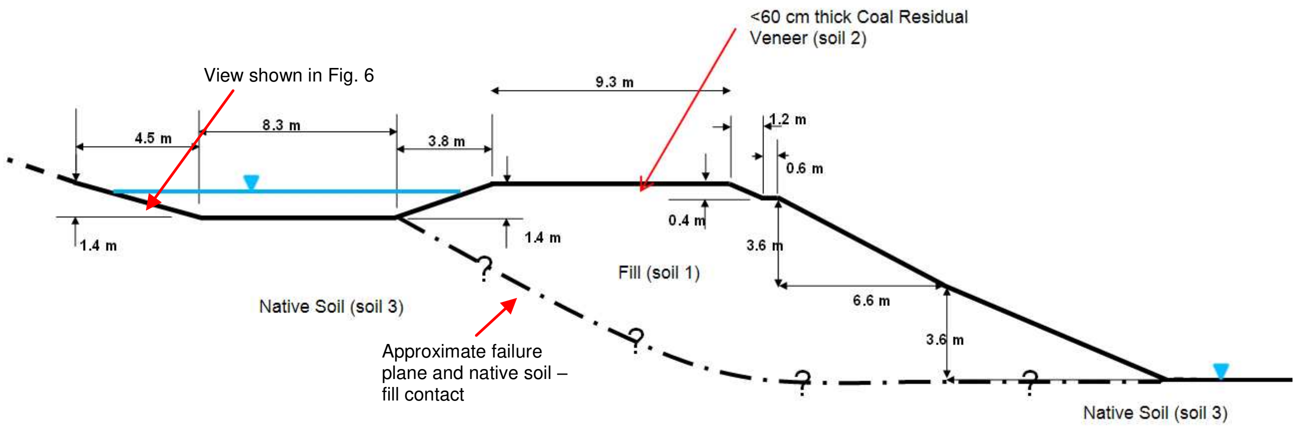


Figure 5. Cross-section of the railroad embankment at the location of the failure.

Description of the Failure

The failure surface appears to engage the entire railroad embankment that is supported on naturally sloping native ground. A 30-m long section of the embankment along the railroad axis slid, and the sliding mass moved a significant distance downslope, removing a number of trees that had grown in the downslope side of the embankment between the railroad embankment and Plymouth Rd. The interpreted failure surface per field observations is shown in Fig. 5 and 7 and is in the vicinity of the contact between the native ground and the embankment fill, but appears to be restricted within the embankment fills and not involve the native soils.

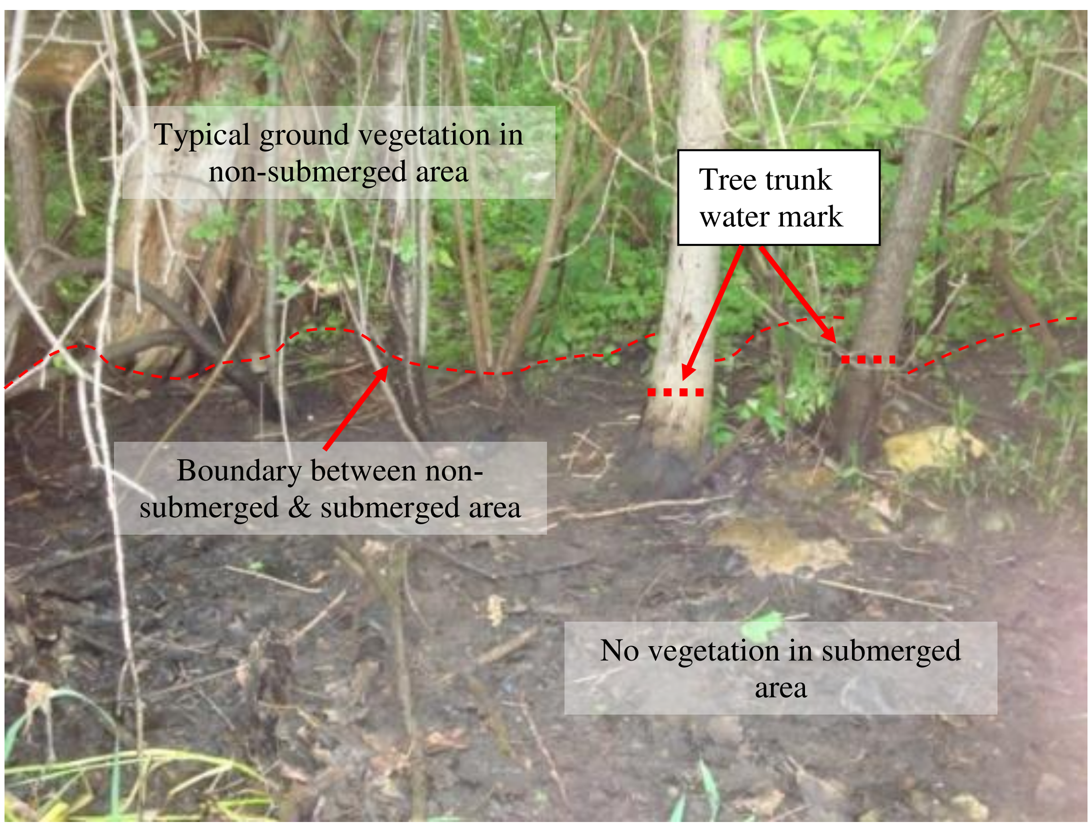


Figure 6. Area previously covered by ponding water and water mark on tree trunks.

Figure 7. View of the failure along, and perpendicular to, the railroad embankment axis.

In-situ and Laboratory Assessment of Soil Properties

In-situ tests and laboratory tests on the bulk samples were performed to characterize the three soils, and assess the hydraulic conductivity and the shear strength of the embankment fill material. The results are briefly presented below:

Soil Layer 1: This soil layer represents the main embankment layer, as shown in Fig. 5, and is classified per USCS as silty sand (SM). 18.9% of the material are non-plastic fines as shown in Fig. 8a. Since undisturbed samples were impossible to collect for the sandy fill, tests were conducted on reconstituted specimens at two different density states to evaluate the range of shear strengths expected for these materials. The direct shear tests were conducted in dry conditions. The shear strength of the material at a dense state was evaluated on the basis of direct shear testing, and the peak friction angle was found to be equal to 46^{o}, whereas the post-peak was found to be equal to 38^{o} without any cohesion, as shown in Fig. 9. The large-displacement friction angle at a dense state is approaching the peak friction angle of the soil at the loose state that was found to be equal to 35^{o}. The hydraulic conductivity of the soil at a dry unit weight of 1.71 gr/cm^3, was equal to $5.1*10^{-5}$ cm/sec based on a falling head hydraulic conductivity test conducted in the laboratory.

Soil Layer 2: This embankment layer is restricted to the top few cm from the surface and is essentially coal ash residuals that are black in color and can be clearly seen in Fig. 10. The fines are non-plastic and represent only 6.8% of the total mass of the soil, whereas the gravelly size particles are equal to 29.6%. It is classified per USCS as well-graded gravelly sand with silt (SW-SM). This soil layer is not expected to have played a significant role in the failure since it is of very small thickness and restricted at the surface only. Thus, more comprehensive testing to characterize its properties was not conducted.

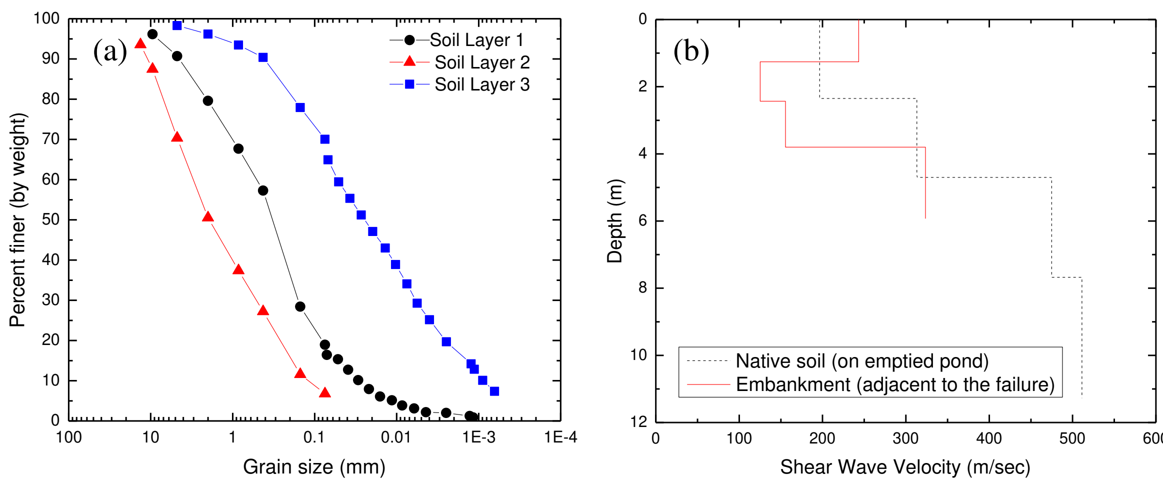


Figure 8. Results of (a) grain size distribution analyses and (b) in-situ shear wave velocity

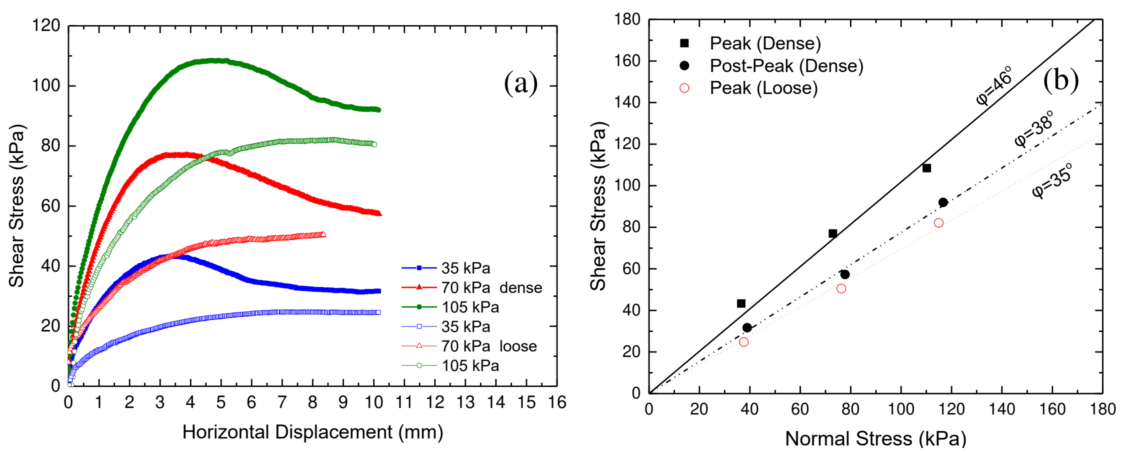


Figure 9. Direct shear results at nominal vertical stresses of 35 kPa, 70 kPa, and 105 kPa on reconstituted specimens of Soil Layer 1.

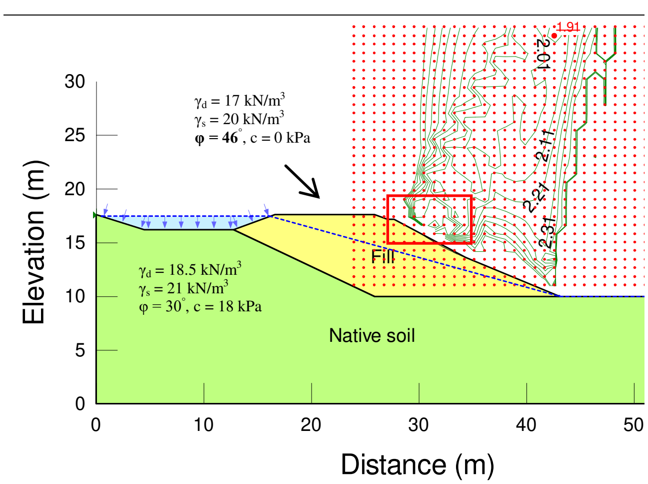
Soil Layer 3: The railroad embankment is supported on natural soil that classifies per USCS as sandy clay of low plasticity (CL) with 70% fines, Liquid Limit 27% and Plasticity Index of 10%. It is important to note that undisturbed samples were not collected to assess the shear strength of the soil, since the native soil does not seem to have been part of the failure surface. This observation is supported by the in-situ measurements of the shear wave velocity of the material that are presented in Fig. 8b, and indicate the material is very stiff and likely to be dense and very strong. The available literature indicates that a reasonable estimate of the shear strength of the compacted clay soil is a cohesion of 18 kPa and a friction angle of 30^o (e.g., indicative values are listed in Table 5.8 of Duncan and Wright, 2005). Analyses indicate that these strength parameters are adequately high to restrict the critical failure in the fill soils of the overlying layers. The hydraulic conductivity of the CL soil was also estimated to be in the order of 10^{-7} cm/sec, based on empirical estimates. It is important to note that in general, site-specific tests are needed to properly evaluate the material properties of each soil unit. However, for this specific unit, reasonable estimates of material properties and parametric stability analyses confirm the field observations that this layer does not appear to be involved in the failure.

Figure 10. View of the failure from the crest of the failure surface where (a) the left-in-place embankment is shown; (b) the mass of soil with large amount of water is shown at the toe of the failure reaching the pre-existing natural stream.

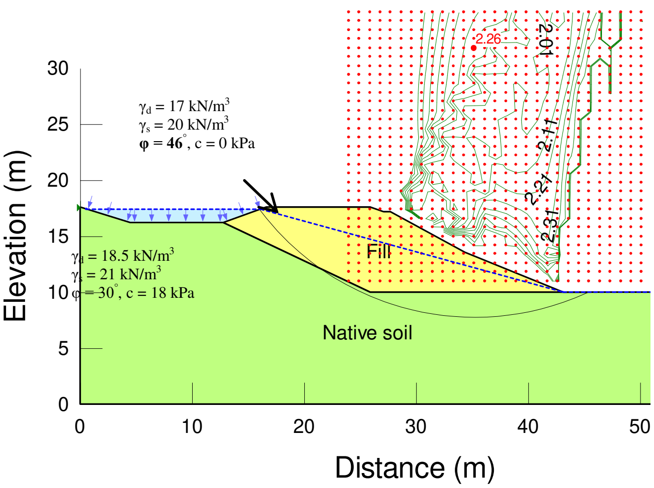
ANALYSES

Initial Stability Analyses

Following site characterization and the assessment of the embankment and failure surface geometry, stability and seepage analyses were conducted using the software programs SEEP/W and SLOPE/W (Geostudio, 2007) and the Spencer method of analysis (Spencer 1967). For stability assessment, parametric analyses were also conducted for reasonable variations of soil properties, as well as variations of the water depth of the ponding water (60 – 120 cm) that is reasonably well documented based on the field observations. These parametric analyses are critical in assessing the impact of uncertainties in the results. The parametric stability analyses indicate that even for the highest ponding water depth, the factor of safety remains significantly higher than one, i.e., it varies between 1.4-1.9 (for friction angles equal to 38^o and 46^o respectively) for a shallow failure surface that is restricted within the embankment, and is shown in Fig. 11a within the red box. Note that although the failure planes shown are "classic" numerical failure surfaces of purely frictional material with zero cohesion, even for low cohesions of 1-3 kPa, the observation that shallow failure surfaces are most critical remains valid. Higher values of factor of safety that vary between 1.5 and 2.3 were calculated for deeper failure surfaces that intersect the native soil (soil layer 3). Example results of the analyses are presented in Fig. 11.



(a)



(b)

Figure 11. Indicative results of embankment stability analyses for hydrostatic pore pressures. (a) showing lowest Factor of Safety (FS) of 1.91 for shallow failure planes (in the red box); (b) showing indicative FS of 2.26 for a failure plane that intersects the native soils.

Stability Analyses Under Conditions of Seepage

Subsequently, seepage analyses were conducted using the estimated hydraulic conductivities. As described earlier, the natural soil has significantly lower hydraulic conductivity than the embankment soils. Thus, the analyses indicate that when the ponding water depth increases, the exit gradients at the toe of the embankment become high, and vary between 0.48 and 0.78, which are dangerously high and close to critical gradients (~0.9). The stability analyses using the calculated hydraulic pressures, indicate failure of the embankment with factors of safety around one, as shown in Fig. 12. Note that this is not surprising as the seepage analysis gives a more realistic pore pressure profile (Fig. 12a) than that of an arbitrarily assumed piezometric surface (e.g., Fig. 11) with the flow concentrating more on the higher hydraulic conductivity soil. The results, indicate that the failure is caused by the high pore pressures that may even cause piping. The numerical results, are supported by the following interesting field observation: The reeds in the ponding water area adjacent to the embankment were found to be bent sideways and positioned horizontally with a direction that was pointing with great accuracy to the exact location where the ponding water initially drained quickly, as shown in Fig. 12.

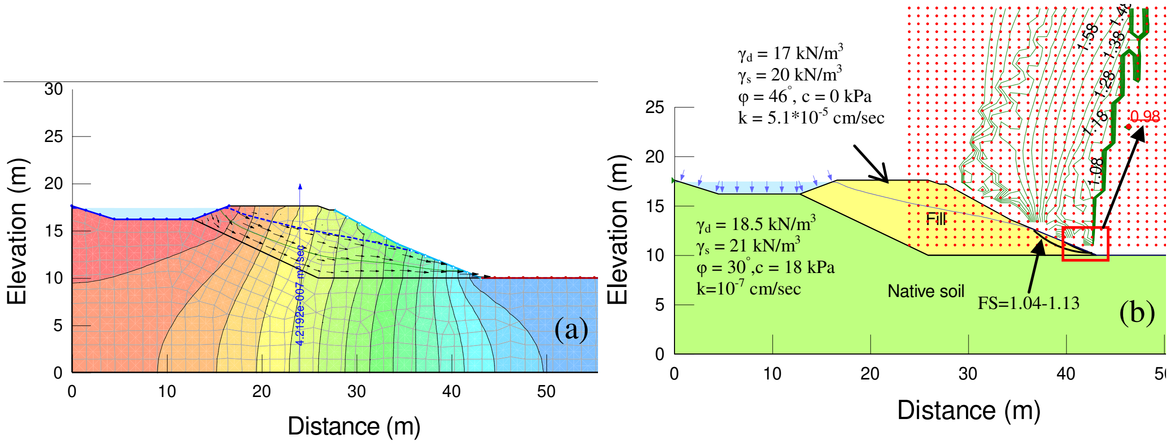


Figure 12. Indicative results of combined (a) seepage and (b) stability analyses using seepage analyses results

Figure 13. View of the failure and the reeds uphill of the embankment. The arrows are parallel to the direction of the fallen reeds that bent and broke during the abrupt emptying of the ponding water and fell on the ground with their orientation pointing to the initiation point of failure. (Fig. 13a by Karl Jansen, ceephotos.com)

USE OF THE CASE HISTORY IN EDUCATION

Available Supporting Material

In the journal's website listing of this paper, electronic supplementary data is provided to readers and is indexed in the following categories:

(a) "Photos, videos and background material" include photos, videos articles, online material and other news media information from the local press related to the case history;

(b) "Characterization Data" include the results of the in-situ and laboratory tests

(c) "Assignments" include a series of assignments that have been used at the University of Michigan to present the case history and assign homework to students; and

(d) "Analysis Files" include Slope/w and Seep/w files with example analyses.

Methodology of Usage of the Case History in Education

For educational purposes, we propose the presentation of the case history to students as a sequence of homework assignments through which progressively more information is provided in an effort to simulate the conditions of a typical consulting project. This sequential approach gives the opportunity to students to appreciate the importance of the assumptions that they make at each stage and their impact on the conducted analyses, as well as the value of the additional data collected. The instructor can vary how much information is provided vs. the amount of work required in homework and adjust the case history to different workloads.

As part of the first assignment, students are requested to collect data about the case history before meeting with the "client". Students conduct research of the available material primarily online, along with geologic and weather data. In the second assignment, the properties of the soils are evaluated. This task can be executed as part of a classroom environment at three different levels: In the simplest level, the final field and laboratory experimental results are presented to the students for synthesis. In the intermediate level, the raw experimental data is provided and the students have to use the data to derive the final experimental results. In the most advanced level that has been implemented at the University of Michigan, students conduct the laboratory experiments to assess the soil properties. The latter level requires the availability of material. For the execution of the stability analyses, slope stability software can be used. Student versions of commercial software or freeware can be adequate. Parametric analyses are conducted for a range of soil properties, and ponding water depths. These analyses provide a first assessment of the impact that various assumptions have on the stability results. Commonly, students are perplexed when the early stability analyses indicate high safety factors. Some of them attempt to "adjust" the numbers, to reduce the factors of safety, without realizing that they lack critical information. In these cases, modeled failures typically do not match field observations, further confusing the students. In the third and fourth part of the assignment, students conduct parametric seepage analyses. The seepage analyses are then combined with stability analyses using the refined, final, soil properties that match the observed failure.

LEARNING OUTCOMES

Case histories, and specifically, the case history of the failure of the railroad embankment in Ann Arbor on May 25 2011, can be valuable in geotechnical engineering education. Students learn:

- The importance of field observations in narrowing and identifying the mechanisms of failure. Analyses without field observations can result in wrong conclusions.

- The importance of reliable assessment of the soil properties through in-situ and laboratory testing.

- The value of parametric analyses in understanding the plausible mechanisms of failure as well as the criticality of assumptions made in the analyses.

- The importance of effective stress theory and the need for seepage analyses to properly characterize hydraulic pressures. As all experienced geotechnical engineers can confirm, among the first questions that a geotechnical engineer needs to answer in performing a failure assessment, or even designing a facility is "Where is the water and where does it go"?

- The importance of monitoring, inspecting and maintaining civil infrastructure, in this case, the railroad embankment.

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