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THE INITIATIVE OF THE HELLENIC SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING TO SUPPORT THE DEVELOPMENT OF CASE STUDIES SUITABLE FOR INSTRUCTION & A SLOPE STABILITY EXAMPLE

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ABSTRACT

The ultimate goal of this article is to promote the collection of case studies suitable for geotechnical instruction by (a) proposing a way of supporting development of such cases through incentives and (b) providing an example of a suitable case study and the necessary accompanying material. The support structure proposed is the initiative of the Hellenic Society for Soil Mechanics and Geotechnical Engineering (HSSMGE) to establish a competition for case studies appropriate for geotechnical instruction and award a prize at its Geotechnical Conference. The paper includes the evaluation criteria and case study specifications of the competition, which highlight the characteristics of case study material suitable for use in instruction. As an example of such a case study, the paper presents a fictionalized narrative related to the design and construction of highway earthworks in Greece and discusses alternative ways in which the case material can be used in instruction.

INTRODUCTION

Case studies have a special place in both geotechnical practice and geotechnical instruction. Implicitly, it appears to be assumed that a case history of interest to practice will also be suitable for instruction. However, this is not always true, as it depends on what instructors aim to achieve by incorporating case studies in a course. If the main purpose is to spice up lectures, provide a motivation for students, etc., then high-profile published case histories, especially dramatic ones involving failures, will do. If, on the other hand, the case study is used for the purpose of achieving specific learning outcomes, which presupposes that the students get actively involved with the case study material and perform some work themselves, then the case study and accompanying material will most likely have to have certain features that distinguish them from a case study contributing to the state of geotechnical practice.

A case study suitable for active involvement of students presupposes complete and easily accessible documentation of all the necessary input data. What is more, the instructor needs to have available rich supplementary material accompanying the case study, including the full set of calculations, annotated with references and comments. Preparing a case study and accompanying material of this type is a time-consuming undertaking, which creates significant additional burden for practitioners. Recognizing both the importance of case studies and the significant workload required on the part of practitioners to put them together, the Hellenic Society for Soil Mechanics and Geotechnical Engineering (HSSMGE) undertook the initiative to provide incentives for the compilation of such cases, as described in the next section.

THE HSSMGE INITIATIVE TO SUPPORT WRITING OF CASE STUDIES FOR INSTRUCTION

The Hellenic Society for Soil Mechanics and Geotechnical Engineering (HSSMGE) will establish an educational case study competition open to practitioners teaming up with a faculty member. The prize will be awarded at the Hellenic Conference on Geotechnical and Geoenvironmental Engineering, which takes place every four years. Candidates for the prize will submit to the HSSMGE an application form, to the Hellenic Conference a brief version of the case in paper format, and will make available the supplementary supporting material in an electronic format. The prize is modest in monetary terms: waiving the fee of the HSSMGE membership for all the authors for a year. It is hoped that recognition will be the main incentive: the prize will be announced in the HSSMGE newsletter and to the HSSMGE membership by e-mail. In addition, the team of the authors will be invited to teach the case as a "Master Class" during a special session of the Hellenic Conference and at Civil Engineering Departments in Greece.

In order for the competition to attract case studies suitable for instruction, its announcement includes explicit evaluation criteria and specifications for candidate case studies. This is necessary information in order to answer the non obvious question "what may be special about case studies used in instruction?". To this end, evaluation criteria are expressed with the aid of the following questions:

(a) Does the case highlight in a paradigmatic way the application of a theory, principle or technique taught in geotechnical engineering courses?
(b) Does the case stress a problem important for practice?
(c) Is the case and supplementary material rich and complete and are they adequately annotated with explanations?

In order for a case to be evaluated for the competition, it must meet the following specifications:

(a) the case should be suitable for geotechnical engineering courses taught in Greek Civil Engineering Departments, preferably belonging in the 5-year integrated undergraduate curriculum;
(b) the development of the case study should correspond to specific learning outcomes (the announcement includes examples from Orr and Pantazidou, 2012), which should be stated clearly in the application and in the paper;
(c) the supporting material should be available in an electronic format and, if the case is awarded the prize, be posted on the HSSMGE website.

Considering that few cases in the literature are accompanied with supporting material for teaching (e.g. Pantazidou et al. 2008; Orr and Pantazidou, 2013), the team of the authors, all members of the HSSMGE and all but one on its governing board, undertook the preparation of a case study that may serve as an example of the competition requirements. This case study and accompanying material are discussed next.

A SLOPE STABILITY CASE STUDY IN ARCADIA

The brief presentation of the case in Table 1 is meant for the instructors who need to decide whether the case study is suitable for their courses, ideally on minimal information. The learning outcomes that can be achieved depend on how the case is used. If the case is presented as a technical narrative, without students performing any work on the own, a suitable learning outcome is "be aware of the professional responsibilities pertaining to geotechnical projects". Alternatively, the case may be presented in parts and students asked to perform some analyses on their own. Part I (see next section) is appropriate even for an introductory geotechnical course, whereas Parts I and II together are suitable for more advanced courses. For the active involvement option, achievable learning outcomes include "identify potential modes of failure" and "apply methods of (slope stability) analysis already covered in course". All analyses discussed herein have been performed for the purpose of the present article.

The case narrative that follows in the next section is written for the students and includes all the material made available to them. The instructor will also have access to additional supporting material described herein in the respective section.

Table 1. Information necessary to match a case with a course and specifics for the Arcadia case study.

Information type	Case specifics
Geotechnical course	Advanced undergraduate, Graduate
Geotechnical topic	Slope stability, back analysis, residual strength
Learning outcome(s)	1. Identify potential critical modes of failure 2. Apply methods of slope stability analyses already covered in course 3. Be aware of the professional responsibilities pertaining to geotechnical projects

Case narrative: "Highway on the move"

Note: In the description that follows, actual findings from geotechnical/geological investigations and reports are embedded in a case narrative developed for education purposes; to this end, the narrative involves fictitious characters of project team members and some hypothesized project tasks.

Where are we?

From the Mediterranean region we zoom onto Greece (see accompanying PowerPoint presentation in supporting material). We are in the prefecture of Arcadia (or Arcady), at the central part of Peloponnese peninsula, where a fertile plateau is surrounded by mountains covered with lush vegetation. In European Renaissance arts, Arcadia was celebrated as an idyllic place of simple, pastoral life.

What is the problem? – Instability of highway earthworks during construction

Things are a little less idyllic in the mid 1990s, time of the construction of a highway going over these mountains, connecting Tripolis, the capital of the prefecture of Arcadia, to Kalamata (as in Kalamata olives…), the capital of the neighboring prefecture of Messinia to the southwest. Problems with embankment instabilities appear soon after construction of earthworks. At about the same time, the management of the project is transferred from the regional level to the ministry of public works in Athens. Due to the change of the original design, which called for a two-lane road, to a four-lane highway, calculations are rechecked for a problematic section of the highway, constructed at an area of colluvial deposits underlain by flysch.

Part I: Stability calculations for representative cross section of earthworks assuming overall stable conditions

As a young engineer in a consulting company working for the ministry, you are asked to do these calculations for a cross section constructed partly on embankment and partly cutting through the colluvial material, as shown in Fig. 1. Geological mapping covers a zone extending from 150 to 250 m on either side of the road. Geotechnical investigation is focused on problematic areas and in areas where large cuttings or embankments are designed. The geotechnical cross section of Fig. 1 is a typical result of such an investigation. The major units are limestone colluvium, about 20- to 35-m thick, and flysch, separated by a zone of clayey weathered flysch.

The water table within the in situ material is expected to be well below the embankment area, close to the weathered flysch. Some perched water within the cut slope is dealt with drainage pipes. Unit weights and shear strength parameters for the materials involved are included in Table 2. The values for the embankment material are considered reliable. However, the values for the colluvium are approximations resulting from the experience gained at the region during the investigation and construction phases.

As you have never before dealt explicitly with geotechnical analysis of earthworks in any of your geotechnical courses, you consult a manual for geotechnical engineering. In relationship to the typical trapezoidal cross section for an embankment [e.g. Burland et al. (2012): Fig. 70.5], the manual states that you are supposed to check for settlement of the underlying material, as well as for slope stability. You discuss the analysis with your supervisor, who advises you to focus on stability issues (and analyze separately the cut slope, the internal stability of the embankment slope, as well as the overall stability of the embankment-parent foundation material), since settlement is mostly going to be immediate.

Table 2. Material properties for earthwork stability analyses.

Formation	c' (kN/m^2)	φ' (°)	γ_{total} (kN/m^3)
Fill	15	28	20.5
Limestone colluvium	20	30	20

Part I: Slope stability analysis results

Calculations show that the cut slope has a factor of safety (FoS) of 1.472, the embankment slope has a factor of safety of 1.992, while the combined embankment/foundation material cross section has a factor of safety of 1.973. Respective values of FoS for dynamic loading are as follows: 1.197, 1.419 and 1.497. The critical failure surface for the case of the cut slope is depicted in Fig. 2 (all the failure surfaces are included in the supporting material, see Figs. S.2a-S.2f).

Since the calculated factors of safety are adequate, your supervisor decides to take your group for a site visit, where you have a chance to see the slope in real life (Fig. 3). There, the group notices deposited material in addition to the area of the cross section you have checked. A geologist colleague points out for you some of the units you encountered in your calculations (see Fig. 3). He also shows you a depression and below it a milder slope in the natural relief of the colluvium underneath the limestone, which could indicate a possible movement in the geological history of the slope.

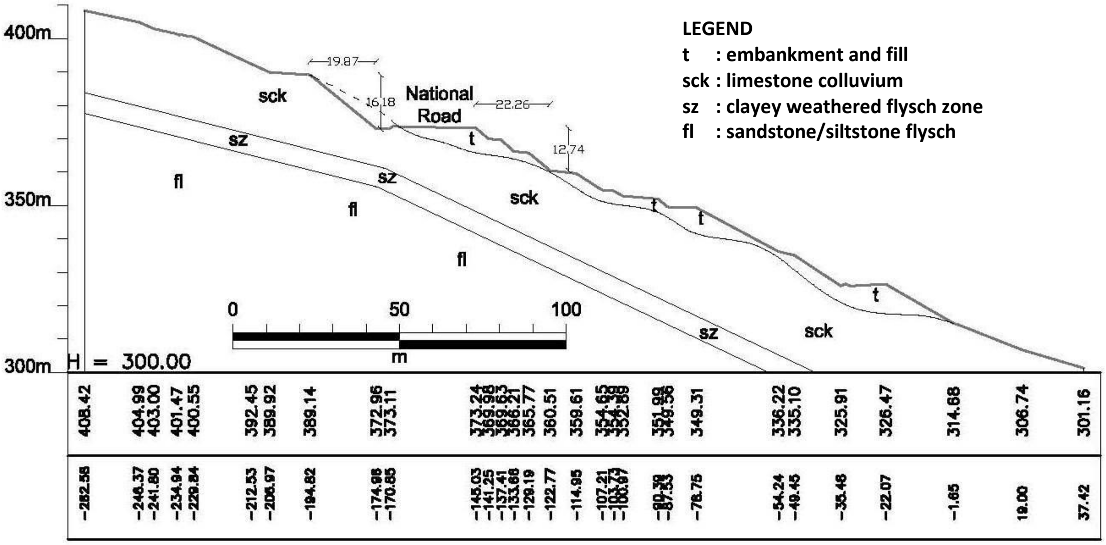

Fig. 1. Cross section of the embankment area.

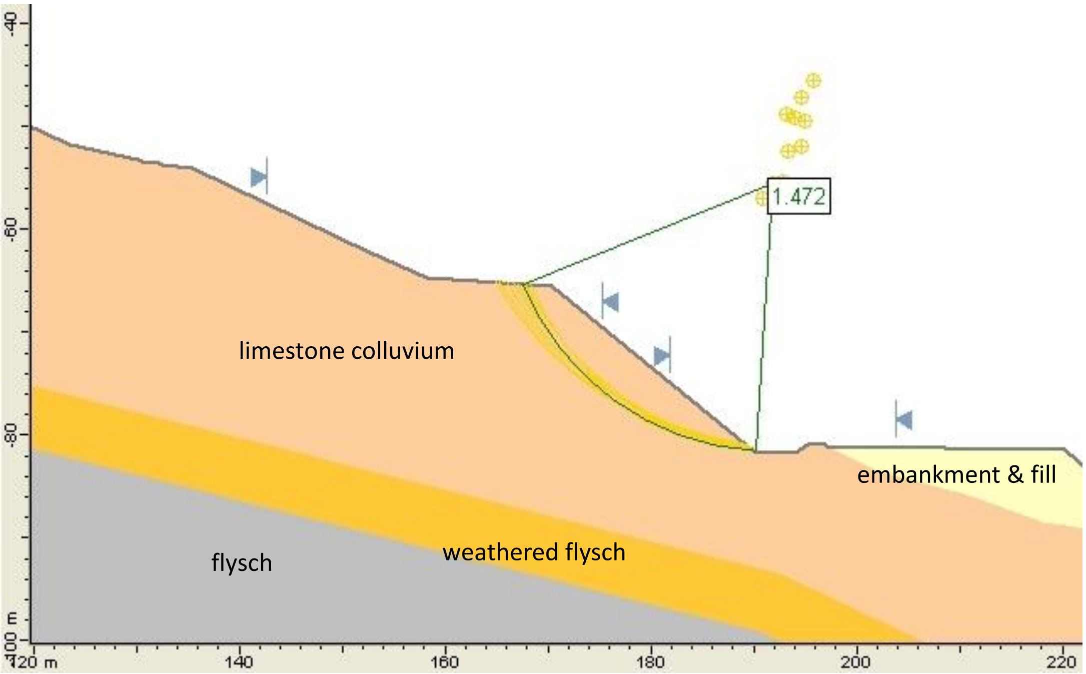

Fig. 2. Critical failure surface of the cut slope, long-term conditions (Bishop method).

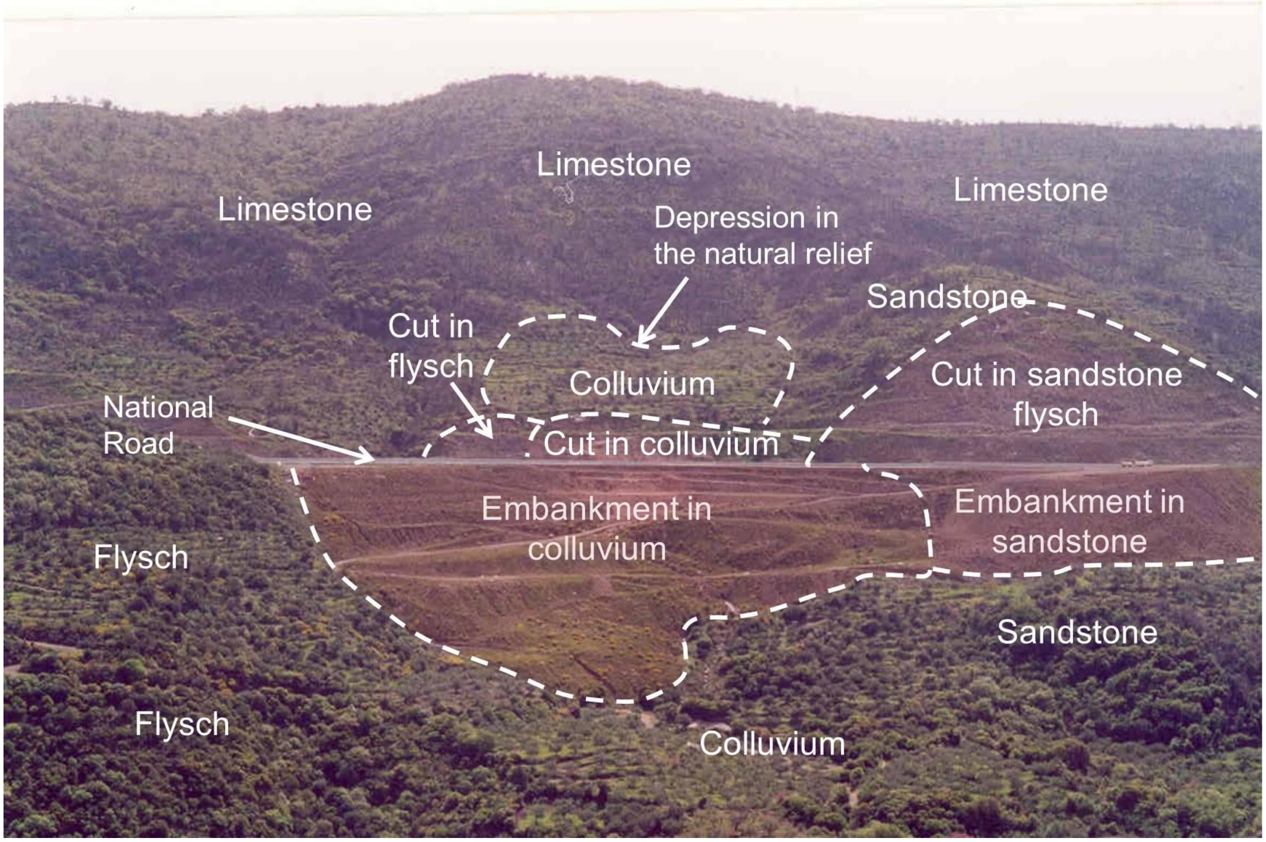

Fig. 3. View of construction area (adapted from Dounias et al., 2006).

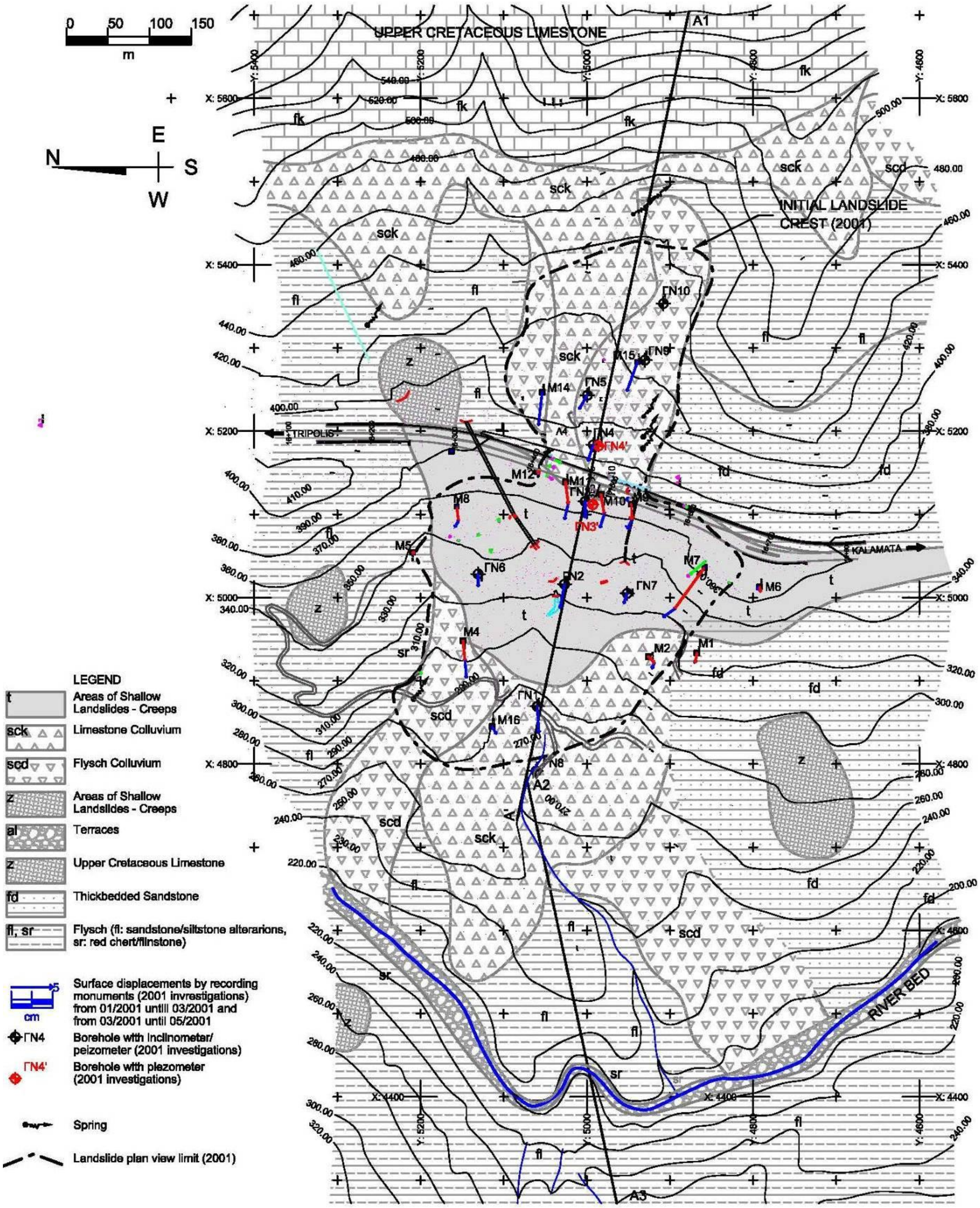

Fig. 4. General plan view with the limits of the slip surface in 2001 and the horizontal surface displacement (adapted from Dounias et al., 2006).

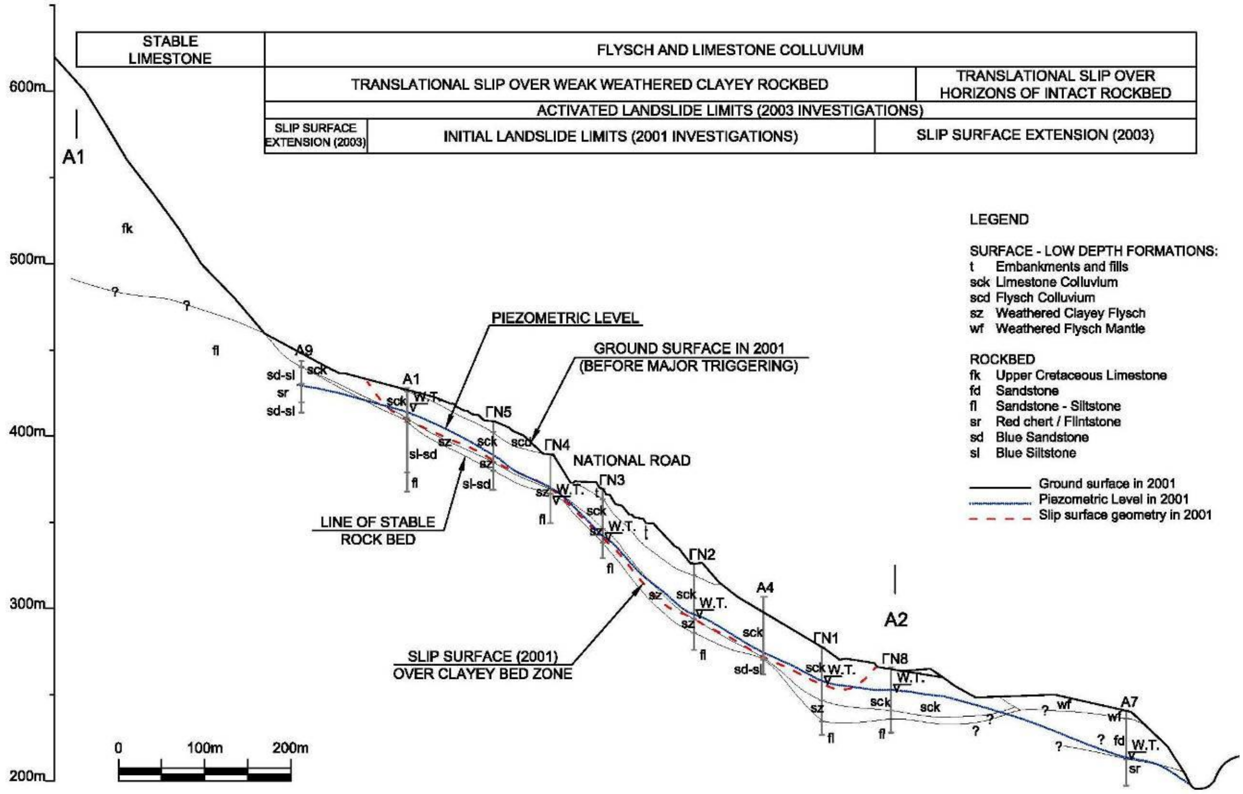

Fig. 5. Cross section of the slip surface in 2001 along axis shown in Fig. 4 (adapted from Dounias et al., 2006).

Highway opens to traffic – problems continue

Construction of pavements was completed in 2000 and the highway opened to traffic. Soon afterwards cracks, perpendicular to the highway axis, and settlements appeared in the pavement, necessitating paving over with asphalt.

As cracks continued to get larger, albeit at a slow rate (Dounias et al., 2006), the ministry commissioned an in-depth site investigation, which included borehole sampling and logging, in situ and laboratory tests, and recordings of inclinometers, surface monuments and piezometers. The investigation was completed in 2001 and established the existence of a sliding surface 680m long and 200m wide at the highway axis, reaching a maximum width of 370m downslope of the highway (see Fig. 4). As shown in Figs. 5 and 6, the main part of the slip surface was located (on the basis of inclinometer readings) within the zone of the weathered flysch (sz), a clayey material of medium to low plasticity, at a variable depth of about 25 to 35m.

Measurements obtained over a period of six months (November 2000-May 2001) gave an average displacement rate of 20cm/year, indicating an active but slow landslide [according to TRB (1996) slides moving at a rate of 1.6mm-1.6m/y are characterized as very slow], which necessitated the evaluation of alternative repair measures. Given the observed movement, the material was likely at a residual state within the slip surface.

Part IIa: Back analysis of cross section of the 2001 slip surface

Back analyses are preformed in order to evaluate the shear strength parameters along the slip surface. Due to the considerable displacement over the aforementioned 6-month period, back analysis for a FoS=1 is expected to give a value of average mobilized shear resistance that corresponds to the average residual strength of the material along the slip surface. Two alternative sliding mechanisms are considered: one single slip surface or two semi-independent slip surfaces, uphill and downhill of the highway, involving areas A1 and A2, respectively, as shown in Fig. 6. The two-section slip surface is the kinematically plausible sliding mechanism suggested by the geometry of the surface of the flysch bedrock (see Fig. 6). As this back analysis is more involved than the one corresponding to the cross section of Fig. 1, you are not expected to perform it on your own. A senior geotechnical engineer discusses with you the analysis for A2 and you are asked to do the same for A1. In both cases, the geometry of the slip surface depicted in Fig. 6 indicates a translational type of slide instead of a rotational (i.e. circular) one.

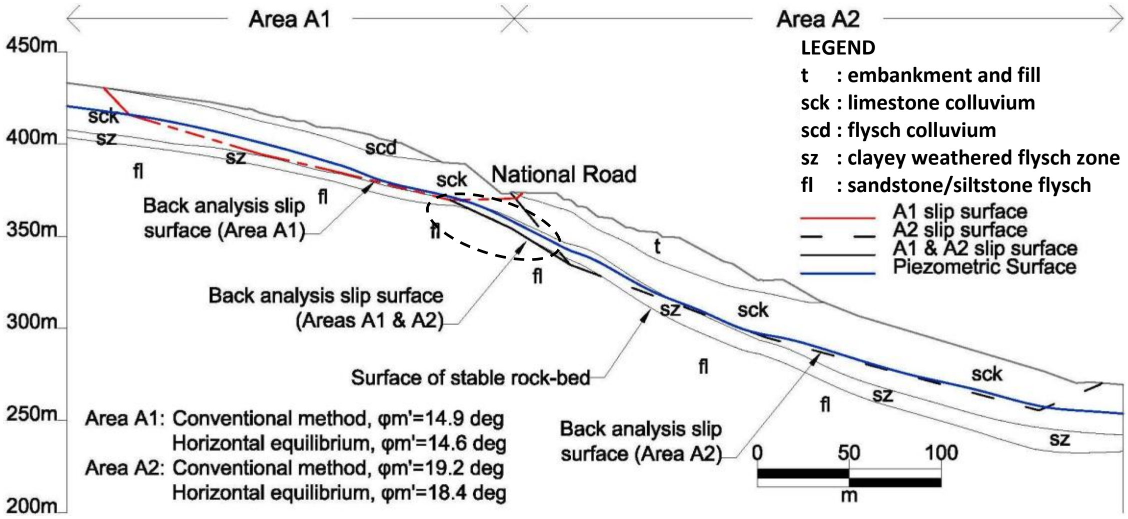

Fig. 6. Cross section showing the two-part slip mechanism along the axis of the slip surface. The dashed-line oval shape highlights the hump in the curvature of the intact/weathered flysch that imposes a kinematic constraint on the failure mechanism.

Note that in the initial calculations for the embankment area, peak shear strength parameters were used. In contrast, for the back analysis, the factor of safety (FoS) is set to 1 and the respective value of the mobilized angle of friction φ_m' is calculated, assuming zero cohesion, c'. For the non-circular failure surface considered in this case, which resembles an infinite slope, the method of slices was combined with two alternative methods for calculating FoS. Method A is known as the conventional method, whereby FoS is expressed as the ratio of the sum of the resisting shear forces on the base of each slice over the sum of the driving forces of each slice's weight resolved parallel to its base (e.g. Equation 12.19 in Knappett and Craig, 2012). For an infinite slope, method A corresponds to calculating the FoS through equilibrium of forces in the direction parallel to the slope. In method B, FoS is calculated through force equilibrium for the entire slope in the horizontal direction (e.g. Equation 5 in Fredlund et al., 1981).

Part IIa: Results from back analysis

The results from the back analysis of area A2 for FoS=1 give a mobilized angle of friction φ_m' equal to 19.2° and 18.4°, with methods A and B, respectively.

You now have to perform the same analyses for area A1 and to back calculate the mobilized strength. You should get values close to $\varphi_m' = 14.9°$ and 14.6°, with methods A and B, respectively. These values will be used to evaluate the feasibility of repair measures, which include excavation (Fig. 7), a grid of stabilizing piles, and anchored retaining walls (Dounias and Belokas, 2010).

Residual strength measurements on soil samples, obtained with the reversal direct shear technique, gave a comparable range for the residual angle of friction $\varphi_r' = 16°$ to 20°. Moreover, samples of this material gave Atterberg Limits of about PL=15% and LL=35%. According to Lupini et al. (1981) and Stark et al. (2005), the values determined for the weathered flysch correspond to the low end of possible values for residual strength, for the measured Atterberg Limits.

Part IIb: Feasibility analysis of excavation as a repair alternative

Your final task for the project is to help the senior geotechnical engineer of the team with the analysis for the repair option with excavation, for sliding area A1 (Fig. 7). Excavation as a repair alternative, in general, aims to relieve the slope from some weight, mainly at the upper part of the sliding area, thereby increasing the overall stability (i.e. FoS) of the slope. In this case, however, the geometry resembles that of an infinite slope, for which FoS does not have a strong dependence on the thickness of the sliding mass. Nevertheless, since the average surface slope inclination and the inclination between berms in Fig. 7 are milder than the inclination of the initial A1 area in Fig. 6, the new geometry could be stable.

Your supervisor advises you to focus on the calculation of overall stability for sliding along the existing slip surface. You will assume that the relevant mobilized angle of shearing resistance along this slip surface is equal to the previously calculated φ_m' through back analysis. First, you will perform a stability analysis for the piezometric level considered in the back analysis. Then, a series of analyses will follow for various values of pore pressure ratio $r_u=u/\sigma_v$, which represents a mean piezometric level above the slip surface (the piezometric level for the back analysis corresponds to a value slightly higher than of $r_u=0$). The new A1 area (i.e. after excavation) has a mean surface slope of about 12°, which results in a theoretical value of r_u of about 0.47 when approximating the slope as infinite and assuming that flow is parallel to the ground surface (Belokas and Anagnostopoulos, 2011). Therefore, the repair alternative can be evaluated for plausible ground water conditions, described by an r_u value varying from 0 to 0.3.

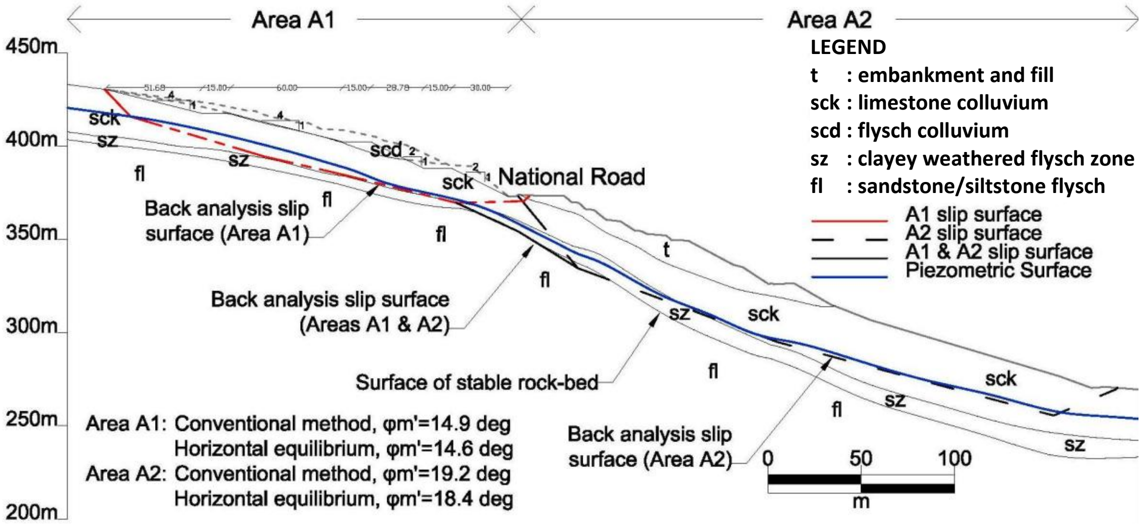

Fig. 7. Cross section showing the excavation in area A1 evaluated as a possible remedial measure.

Part IIb: Results from repair alternative analysis

The calculated FoS assuming the piezometric level used in the back analyses is 0.961 and 0.973, for the conventional and the horizontal equilibrium methods, respectively. In other words, the slope is even more unstable after excavation! This unanticipated finding is likely a result of the reduced height of the sliding mass for the same piezometric level, i.e. of the higher percentage of saturated soil within the sliding mass. Hence, analyses were performed for only a small range of r_u values, in order to investigate the effect of further draining of the slope. The results are given in Table 3 and show that the slope is marginally stable even when fully drained (r_u=0) and, hence, excavation is not a viable repair alternative.

Table 3. Calculated factor of safety for area A1 assuming an extensive excavation, using the activated slip surface, residual shear strength and small r_u values.

r_u	0.00	0.05	0.10
FoS (Conventional Method)	1.082	1.023	0.965
FoS (Horizontal Equilibrium)	1.080	1.022	0.964

What happened at the end?

During the heavy-rain winter of 2003, the pavement suffered considerable settlement in January, which soon developed into a large pothole (Fig. 8). Cracks were enlarged, and increased flow rates were recorded in the drainage system of the slope. In early February 2003, with rainfall continuing, a rapid movement of earth material took place, cutting through a 200m section of the highway. Movements continued over the next several days. When the sliding mass reached a resting position, the pavement had moved 100m horizontally and dropped 40m vertically (Fig. S.9 in the supporting material). The extent of the 2003 failure on the cross section is shown in Figs. S.4c and S.5b of the supporting material. The limits of the landslide extended further downslope to the riverbed (shown in Fig. 4), reaching approximately 1km length.

Fig. 8. Large pothole at the problematic section of the highway (from Dounias et al., 2006).

Due to the large volume of the sliding mass, the repair alternatives were more costly and more uncertain than bypassing the unstable area altogether. Two such solutions were considered, a tunnel behind the unstable mass, going through the flysch stable bedrock and below the slip surface, and a bridge, with a span of 300 m to ensure the foundation of bridge piers on stable material. At the end, the bridge was selected as the most economical solution.

Lessons learned (in hindsight)

- Changes in design, construction provisions and overseeing authorities mid-way in a project create heightened communication needs to address potential communication gaps.

- Some observations before the final rapid soil movement provided "hints" of the developing problem: the milder slope indicates a transition to a less competent material, while cracks perpendicular to the road axis point to a slide, either first-time or reactivated. However, it is a very tough decision for an engineer to halt construction or request additional costly investigations on the basis of such hints alone.
- Careful observations of the natural relief can provide clues of past earth movements, which may recur. Often these observations are meaningful at a scale larger than the area immediately affected by the geotechnical project at hand. Clearly, this is knowledge gained in hindsight, which underscores the usefulness of case studies in helping notice things in another project.
- Average rates of displacement measured for just a few years cannot be used to predict future displacements, particularly if they are not linked to rainfall records. In this case, a prolonged very wet season most probably provided the trigger for the large movement.
- Although the displacement rate measured during the 2000-2001 investigation was low, it could not be dismissed since an acceleration of the movement is more probable in a modified environment compared to a natural one. It could be argued that if immediate deep drainage measures were applied, they might have delayed the evolution of the slide and reduced the possibility for the major triggering until permanent repair measures were in place.

Supporting material

The purpose of the supporting material is to help students become more familiar with the project area and provide to instructors rich supplementary material so that they feel comfortable using the case study in their course. It includes the following:

(a) a PowerPoint presentation with information on the site region and vicinity,
(b) figures related to geotechnical analyses and investigations, including these of this paper in better resolution,
(c) files with the coordinates of the features of all the cross sections analyzed (DXF) as well as corresponding PDF files,
(d) for Parts IIa and IIb, the specific equations used and the EXCEL files with the information on the slices, the ground water level and the computed FoS for areas A1 and A2.

It is noted that the results from the back analyses presented herein (Part IIa) using a spreadsheet program are comparable with the results presented by Dounias and Belokas (2010) and Dounias et al. (2006), which were obtained using a commercial limit equilibrium software package. Concerning the calculations of Part IIb, the excavation geometry is similar to the one presented by Dounias and Belokas (2010).

The supporting material is currently available at http://users.ntua.gr/mpanta/TeachingEN.htm, while in the future it will also be accessible through the website of the HSSMGE (http://www.hssmge.gr/).

Notes to the instructor

The different parts of the case provide different opportunities for the students' active involvement with the case. In part I, the explanation for the possible geometries for the failure surfaces may be omitted from the student version of the narrative, depending on the intended learning objectives, i.e. if the instructor wishes the students to focus on identifying possible modes of instability failure. In part II, the instructor may ask the students to perform the calculations for area A1, after (i) providing the students with the equations employed in methods A and B, or (ii) discussing at some length the approach in class, or (iii) sharing with students the supporting material for area A2. The analyses can be performed either by hand calculations or by programming the limit equilibrium equations into a spreadsheet program, depending on the objectives of the instructor.

CONCLUDING REMARKS

When instructors wish to use cases to actively involve the students and achieve specific learning outcomes, they need extensive yet concise case documentation, which is typically not available in peer reviewed publications describing cases. Hence, instructors are limited to the cases from their personal experience. Establishing a tradition of preparing educational case study material will help expand the repertoire of all instructors. Such undertaking requires significant effort, hence it needs to be supported with incentives. This paper described the initiative of the Hellenic SSMGE to provide such an incentive to its membership, by awarding prizes to well selected and carefully documented case studies for instruction. It is hoped that other geotechnical societies undertake similar initiatives, helping produce a rich database of geotechnical case studies specifically written for instruction.

The slope failure presented herein as an example of a case study suitable for instruction underscores the usefulness of case studies with its ultimate "lesson learned". The challenge of the geotechnical engineer is often two-fold: not only to identify the potential for the instability of the larger area (at the stage of earthwork construction, in this particular case), but also to make a convincing argument (in the absence of conclusive evidence) that additional investigation is warranted, incurring additional costs and delays. Similarities with existing cases strengthen such an argument.

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