Chapter 2
Forensic Geotechnical Engineering
Theory and Practice

Suzanne Lacasse

Abstract Geotechnical engineers working with forensic evaluations must apply science and engineering within the rules and practice of the legal system, in order to be effective in representing reality and resolving conflicts. Such rules and practice will vary from country to country. The geotechnical work required for the documentation of forensic cases, however, should observe the same standards of quality in all countries. To provide the required assistance in the settlement of disputes, the engineer needs to combine high quality forensic investigations consistent with good science and engineering with an ability to clearly present the matters being disputed. This keynote lecture reviews the basic requirements of forensic geotechnical engineering. The technical forensic investigation requires collection of data, problem characterization, development of failure hypotheses, a realistic back-analysis, observations in situ and in some cases performance monitoring, and most importantly quality control of not only the formal but also the technical aspects of the work. Two case histories of landslides are presented. The role of the geotechnical engineer as a forensic expert is highlighted, in particular in investigating damage and failure, evaluating the hazards and consequences, developing repair recommendations and preparing reports.

Keywords Forensic · Risk · Expert witness · Standard of care

2.1 Introduction

The practice of forensic geotechnical engineering is the application of geotechnical engineering to answer questions pertaining to a conflict in the legal system. The word forensic comes from Latin, where forensic means “of” or “before the forum”. In Roman times, a criminal charge required presenting the case in a forum before a
group of public individuals. The individual(s) with the best argument and delivery would determine the outcome of the case. The modern usages of the word forensic are a form of legal evidence and a category of public presentation (Lucia 2012).

The basic book on forensic engineering, “Forensic Geotechnical and Foundation Engineering” by Day (2011), interestingly, begins with the example of the sanctions in the legal code of construction of the great Babylonian King Hammurabi. Two sanctions are illustrated in Fig. 2.1. Fortunately for our profession, the times and the legal codes have changed! Even more impressive, the code makers understood about risk, where Risk includes the Hazard and the Consequence components of an event.

Geotechnical engineers must apply science and engineering within the rules and practice of the legal system in order for their work to be effective in representing reality and resolving conflicts. Such rules and practice will vary from state to state and from country to country. However, the geotechnical work required for the documentation of forensic cases should observe the same standards of quality in all states and countries. To provide the required assistance in the settlement of disputes, the geotechnical engineer needs to combine high quality forensic investigations consistent with good science and engineering with an ability to clearly present the matters being disputed. The technical forensic investigation requires collection of data, problem characterization, development of failure hypotheses, a realistic back-analysis, field observations and in some cases performance monitoring, and most importantly quality control of not only the formal but also the technical aspects of the work.

---

Fig. 2.1 Sanctions in construction code in old Babylonia

1The Code of Hammurabi is a Babylonian law code dating back to about 1772 BC, and is one of the oldest writings in the world. The sixth Babylonian king, Hammurabi, enacted the code. The Code consists of 282 laws, with scaled punishments, adjusting “an eye for an eye, a tooth for a tooth” depending on social status (slave versus free man). Nearly one-half of the Code deals with matters of contract, establishing for example the wages to be paid to an ox driver or a surgeon. Other provisions set the terms of a transaction, for example, the liability of a builder for a house that collapses, or property that is damaged while left in the care of another.
Issues that have arisen requiring a forensic geotechnical analysis include for example (Day 2011): expansive soils, collapsible soils, settlement of shallow and deep compacted fills, moisture intrusion, corrosion, exposure to sulphates, runoff and drainage, pavement failures, slope instability, foundation failures, excavation failures, “differing” site conditions and underground pipeline failures.

The keynote lecture reviews the basic principles of forensic geotechnical engineering. Two case histories of slope instability, illustrating the importance of thorough and extensive geotechnical investigations and analyses, are presented. The first case study exemplifies how information from geological, geophysical and geotechnical investigations was integrated to establish a realistic model of the slope instability and to establish the trigger of the slide. This case ended up in court. The second case study tells an abridged story of the Storegga slide, one of the largest known underwater slides on earth. The role of the geotechnical engineer as a forensic expert is also highlighted, especially in preparing evidence and explaining the evidence in a clear manner.

2.1.1 The Practice of Forensic Engineering

The principles presented herein are based on the excellent review prepared by Lucia (2012) as part of the State-of-the-Art and State-of-Practice in Geotechnical Engineering GeoCongress in Oakland California USA.

In litigation, forensic engineering contains components of legal evidence and public presentation. The ability to present complicated technical facts to a layperson is the key to the outcome of a conflict. Unfortunately, facts are only a part of the resolution of a conflict. A poor presentation of the facts, in some case a distorted presentation of the facts, can determine the outcome in a direction that does not agree with the engineering state-of-the-art.

The evaluation of a failure in the case of litigation has to incorporate the laws of science, the practice of engineering and the rules of evidence within a court system.

The forensic evaluation leads to an opinion on the cause of a failure and then to the responsibility for that cause. The technical evaluation leads to an assignment of responsibility to a party.

Engineers are typically ill-equipped to deal with the forensic process. Lawyers on the other hand are skilled at the presentation of facts and the resolution of conflicts.

2.1.2 Standard of Care

The engineer’s compliance to the “standard of care” is usually one of the main issues in the case of litigation. ASFE (1993) stated that the standard of care is “that level of skill and competence ordinarily and contemporaneously demonstrated by professionals of the same discipline practising in the same locale and faced with the same
or similar facts and circumstances”. Parties in litigation therefore look for factors that contributed to the failure that are not representative of the standards met by other engineers (including sampling, in situ testing, laboratory testing, type of analyses, assumptions made, recommendations and performance monitoring). The courts do recognize that the standards and practice of engineering can vary over time.

Because there are never complete data to describe a site, the geotechnical engineer must interpolate between the limited data, apply assumptions to an analysis, make recommendations based on the interpolations and assumptions, and possibly include a monitoring programme. All of these steps require “substantial judgment” (Lucia 2012). While extreme cases do happen where causes and effects are obvious, most of the time the evaluation of the compliance with the Standard of Care by engineers fall into a grey area which very often results in a difference of opinions between experts. The standard of care is never written down in a manner that has gained universal acceptance, and is therefore always subject to debate. The combination of science and empiricism is considered the definition of the Standard of Care (Lucia 2012).

### 2.1.3 Expert Evidence

The forensic evaluation is intended to come to an opinion as to the factors that led to the failure and were ultimately responsible for the failure. Lucia (2012) reported that the USA Supreme Court ruled that the judge must ensure that any and all scientific testimony or evidence admitted is both relevant and reliable. The rules of admissibility are based on four criteria:

- When a scientific theory or technique is used in the development of an opinion, has the theory or opinion been tested?
- Has the scientific theory or theory been subjected to peer review and publication?
- Are there standards to control the application of the scientific theory or technique, and is there a known or potential error rate?
- Has the scientific theory or technique gained acceptance within the relevant scientific community?

Knowledge needs to be more than subjective belief or speculation, and must apply to a body of data or facts. Expert testimony does not need to be accurate with 100% certainty. It is recognized that uncertainties exist in science and engineering.

### 2.1.4 Forensic Investigation and Litigation Process

The process begins when the parties realize that something different than assumed by the engineer has occurred. The question is, for example, whether the situation could have been foreseen, was knowable, was the result of an error in calculations,
an omission, a negligent act on the part of the engineer, or a defect in construction caused by the contractor.

The burden of proof is on the plaintiff to demonstrate that the geotechnical engineer breached the Standard of Care.

After forensic investigation has been completed by both sides of the litigation, the process of financially resolving the conflict begins. The decision of a settlement or a court case is generally a business decision, including the consideration of the costs yet to be incurred and the risk of losing. Lucia (2012) reported that 90% of all the litigation cases he has been involved in have been settled prior to trial.

### 2.1.5 Case Studies Presented by Lucia (2012)

Lucia (2012) presented two examples of how the quality of the expert testimony can determine the litigation outcome. Central facts are summarized in Table 2.1.

The one lesson learned from these two case studies is that convincing a jury or a judge in a case involving technical matters depends on presenting the best facts supporting the case in such a way that a layperson can understand. No matter how correct a theory can be, a layperson will not be convinced unless he/she can understand its effects. Often an analogy, e.g. with a simple physical demonstration, will end up in being the most effective tool.

<table>
<thead>
<tr>
<th>Case no./description</th>
<th>Outcome/comments</th>
<th>Ruling</th>
<th>Expert testimony</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground settlement after trenching for utility installation. Owner demanded that the contractor remedy to the defect. Mediation failed, and the case ended in court</td>
<td>Contractor did place the fill according to contract specification, but the contract specification was inadequate. Should the engineer have reviewed the specification before start of the work?</td>
<td>Jury ruled in favour of contractor</td>
<td>Good facts, good presentation (simple demonstration of wet and dry densities) The technical issues were narrow and were made easily understandable to jury</td>
</tr>
<tr>
<td>Shallow failures (landslides) in open spaces in large housing complex. Homeowner association sued developer and contractor. Repair costs estimated by opposing experts to USD 2.5 and 25 M</td>
<td>Technical issues debated: – Extent and residual strength of colluvium; – Assumptions on water level; – Effect of earthquake loading; – Appropriate factor of safety (1.25, 1.5 or &gt;1.5?)</td>
<td>Jury ruled USD 6.5 M compensation to be paid by developer and contractor to homeowners</td>
<td>Good facts, bad presentation by experts on both sides Jury members told afterwards that they did not understand what the experts on either side were talking about, and did not know who had the best facts</td>
</tr>
</tbody>
</table>
2.2 Case Study I

2.2.1 Finneidfjord Nearshore Shallow Landslide

2.2.1.1 Description of Case Study

In June 1996, a landslide of over 1 million m$^3$ occurred just off the shoreline near the village of Finneidfjord in Northern Norway. During the Holocene, the marine deposits were exposed to freshwater flow and the leaching of salts resulted in very sensitive clays, called quick clays. The initial failure was believed to have occurred on the steepest slope of the foreshore (Janbu 1996; Longva et al. 2003; Gregersen 1999). Although 90% of the slide was below sea level, its retrogressive nature meant that while encroaching 100–150 m inland, it destroyed 250–300 m of the Norwegian E6 highway and three residential houses (Figs. 2.2 and 2.3). Tragically four persons were killed, one in a car on the highway and three persons in one of the houses.

Geotechnical investigations prior and subsequent to the slide revealed large volumes of quick clay in the area. The Finneidfjord landslide developed along a well-defined plane. Based on seismic reflection and core data, the slip plane was identified as a stratigraphically weak, laminated, clay-rich bed (L’Heureux et al. 2012a, b; Steiner et al. 2012). The combined geophysical and geotechnical investigations indicated a complex, multi-stage failure.

A fill, from the excavated material for a nearby tunnelling project, was placed on the foreshore of the embankment just before the failure (Fig. 2.2). Blasting in the area had also taken place prior to the slide. In addition, intense rainfall had occurred in the days prior to the failure.

2.2.1.2 Post Failure Investigation

High-resolution swath bathymetry 2D reflection seismic profiles, a decimetre-resolution 3D seismic volume, numerous short cores, two long cores, and Free Fall cone penetrometer (FF-CPTu) profiles were used. The overlapping multi-beam bathymetric data sets were collected in the area between 2003 and 2009 (Vardy et al. 2012).

The geophysical data were complemented by geotechnical tests. Multi-sensor core logging (MSCL), detailed sedimentological description and X-ray imagery were used to describe structure, stratification and composition. The tests yielded magnetic susceptibility; density; P-wave velocity; porosity and water content; and grain size distribution. In situ geotechnical data were also acquired using free-fall CPTu. A total of 38 individual drops were done (Steiner et al. 2012).

Swath bathymetry images revealed evidence of mass wasting at several locations in the area. The landslide scars are 2–3 m high and devoid of debris, with the smooth surface interpreted as exposed slip planes. The planes correlate to a well-defined and high-amplitude reflection in high-resolution sub-bottom profiles (Fig. 2.4). This high-amplitude reflection was mapped throughout the fjord basin.
The bathymetry and seismic data and sediment cores showed that many of the underwater slides in the area were initiated along these “weak” beds (L’Heureux et al. 2012a). This includes the landslide of June 1996 (Fig. 2.3). Stage numbering in Fig. 2.3 refers to the phases of landslide development identified by Longva et al. (2003).

Fig. 2.2 Area prior to the Finneidfjord submarine slide (Gregersen 1999)

Fig. 2.3 Surface morphology for 1996 landslide imaged using high-resolution swath bathymetry (Vardy et al. 2012)
A two-stage mechanism describes the failure: the initial phase was a transitional movement of the foreshore slope; the second stage involved blocky debris flow deposition as the head wall retrogressed to the shoreline and beyond.

Figure 2.5 shows the results of seismic and geotechnical investigations. The upper part of the figure shows seismic evidence for the slip plane (weaker layer) as a composite seismic reflection event that is partly eroded underneath landslide debris. The lower part of Fig. 2.5 shows the results from piston core, laboratory analyses and free-fall CPTu tests (L’Heureux et al. 2012a).

The soil recovered in piston cores pushed adjacent to the slide deposit contained essentially homogeneous silty clays with shell fragments. The lithology changed suddenly at 2.9 m depth where a 45 cm thick bed, consisting of a 5 cm thick sand layer sandwiched between two distinct grey clay layers, 20 cm thick, was observed, with lows in both magnetic susceptibility and gamma density, and a very sharp peak in magnetic susceptibility and gamma density for the sandy layer. These features were confirmed by the free-fall CPTu tests. The water content for the laminated silty clay averaged 35 %.

In contrast, the water content was higher in the inferred failure zone, typically 45–65 %. Undrained shear strength ($s_u$) were typically lower (4–8 kPa), whereas the ratio of undrained shear strength to effective vertical stress ($s_u/\sigma'_{vo}$) fell between 0.2 and 0.3, which is a reasonable value for a normally consolidated clay. In contrast, the ratios $s_u/\sigma'_{vo}$ for the background silt exceeded 0.3.
2.2.1.3 Deterministic and Probabilistic Analysis of Slope Stability

An initial deterministic stability analysis was run along the steepest cross section in the region surrounding where a fill had been placed (Fig. 2.2). There was consensus that the slide was initially triggered in this north-west region (Janbu 1996; Gregersen 1999; Longva et al. 2003), based on eyewitness accounts of waves, bubbles and whirls moving away from the shore and sea bottom investigations. The stability analysis used the Morgenstern-Price method with the SLOPE/W software. The initial deterministic failure mechanism investigated is shown in Fig. 2.6. For the properties and geometry assumed, the slope was found unstable with a safety factor of 0.95.

The initial deterministic analysis predicted that the slope cannot hold even though it was actually standing before the fill was placed. Geometrically lower slope steepness, higher soil strengths or model bias can explain such apparent
inconsistency. Introducing the weaker layer seen on the geophysical traces would bring the deterministic safety factor even lower. Cassidy et al. (2008) explored probabilistically the implications of the placement of the fill shown in Fig. 2.2. As shown in Fig. 2.7 and the top (black) curve in Fig. 2.8, increased layers of fill reduced the safety factor and the stability of the slope, with the mean calculable factor of safety against failure reducing from 0.95 to 0.91 and the probability of failure increasing to 80 %, as the fill increases to a height of 2.5 m.

Mean values for the probabilities of failure were studied as a function of varying fill height. However, it is known that the slope was standing under the condition of “no fill”. Under the assumption that the placement of a fill is the only triggering mechanism, the probability of failure was again calculated.

![Fig. 2.6 Failure mechanism in deterministic analysis of Finneidfjord slide (Cassidy et al. 2008)](image1)

![Curves move towards left as fill height increases](image2)

![Fig. 2.7 Probability of exceeding factor of safety (FoS) of unity in probabilistic analysis for increased fill heights (Cassidy et al. 2008)](image3)
The probability of slope failure given an initially stable slope was described as:

\[
P(\text{FoS} < 1 | \text{FoS}_{\text{nofill}} \geq 1) = 1 - \frac{P(\text{FoS} \geq 1)}{P(\text{FoS}_{\text{nofill}} \geq 1)}
\]  

(2.1)

where FoS is the factor of safety. These results of the probabilistic analyses are shown in Fig. 2.8. The analysis suggests that by including the known fact that the slope was originally stable, the probability of failure increases from close to 0 to just over 40% with a 2.5 m high fill (blue curve in Fig. 2.8). The increase is not linear, with initially very little effect from adding more fill, but then also tapering off between the 2 and 2.5 m scenario results. The safety was therefore marginal \((P_f \approx 40\%\) with the addition of a 2 m fill. Cassidy et al. (2008) also assessed the vulnerability and consequences of the Finneidfjord slide.

2.2.1.4 Possible Triggers for Finneidfjord Landslide

For the 1996 landslide near Finneidfjord, the identification of key reflections in the geophysical investigations indicated that the glide plane for the 1996 landslide may lie within the upper clay layer. This agreed with short cores higher up the foreshore slope that sample the exposed glide plane. In these cores, the sandy and lower clay layers were preserved. The upper clay was still present, but significantly thinner than observed in cores recovered adjacent to the slide (L’Heureux et al. 2012a). While the physical properties of the weaker material depended on the formation processes (i.e. rapid deposition of sensitive clay-rich material), it is unlikely that this alone made the layer weak enough to fail.
Post-depositional factors such as shallow gas and/or fluid flow and other external factors may have played a role in the triggering of the failure of the Finneidfjord slope. The following factors may have contributed as pre-conditioning factors to the landslide: excess pore pressure as a result of climatic and anthropogenic factors or the accumulation of free gas (Best et al. 2003; Morgan et al. 2009). The increase in overburden stress due to alongshore placement of fill material (Gregersen 1999) and the blasting from a nearby construction project (Woldeselassie 2012) could have acted as triggers. Recent numerical simulations showed that vibrations could have caused a slight increase in pore pressure (2–3 kPa) in the weaker silty clay layer. In the present analysis, the placement of 12,000–15,000 m$^3$ of fill from a nearby tunnelling project on the foreshore of the fjord was investigated as a possible trigger for the slide. Research studies are still ongoing on the possible triggers for the Finneidfjord landslide. Since the stability of the slope was initially marginal, several factors could have triggered the failure, or most probably, a combination of factors may have contributed to the failure.

The integration of geological and geophysical data was probably indispensable to construct a complete picture of all aspects influencing the conditions of the Finneidfjord slope, but also other instabilities in similar settings. The geophysics revealed the occurrence of a composite reflection of a thin sandy unit sandwiched between two clay units, which is new information. Similar identifications have been made in other fjords as the result of terrestrial quick-clay landslides in the catchment of the fjord, both in Norway and Canada (L’Heureux et al. 2012a). The stability analyses herein were done before all the geophysical information became available, and do not account for the presence of the effect of the weak layer. The weaker layer would change the shape of the slip plane, resulting in a lower safety factor and a higher probability of failure.

The jury involved in the litigation case concluded in disagreement with the placement of 12,000–15,000 m$^3$ of fill on the foreshore of the fjord being the trigger for the slide, and ruled that the cause of the failure could have been an increase in the pore pressure in the clay (at the time, the increase in pore pressure was still unexplained). The reason for this conclusion was the jury believing one of the experts more than the other one, probably because of a more forceful and more convincing presentation by this expert and the lawyer.

2.3 Case Study II

2.3.1 The Story of the Storegga Slide

The Storegga slide at the Ormen Lange site is one of the largest known submarine slides on earth. The head wall of the slide scar is 300 km long. About 3500 km$^3$ failed from the shelf edge, sliding out as far as 800 km in water depths as deep as 3000 m (Fig. 2.9). The failure started probably some 200 km downhill and crept
rapidly upwards as the headwalls failed and slipped down towards the deep ocean floor. At the same time, the mass movement generated a huge tsunami that reached the shores of, among others, Norway, Scotland and the Shetland Islands. The sizable gas resources at Ormen Lange are located in the scar left by the giant underwater slide, beneath a relatively chaotic terrain created by the slide 8200 years ago.

The Storegga was not the subject of litigation, but it was the subject of a large, probably unprecedented, integrated study for the safe development of the deepwater gas field at the Ormen Lange site on the North Atlantic continental margin. In addition, the SEABED project was launched by the partners of the Ormen Lange field (Norsk Hydro ASA, A/S Norske Shell, Petoro AS, Statoil ASA, BP Norge AS and Esso Exploration and Production Norway AS) with the aim of improving the knowledge of the seafloor morphology, the shallow geology, and the potential hazards and risks associated with the area. The aim was to quantify the risks, reduce them as much as possible and ascertain any possible risk to third parties.

The project is an excellent example of the interweaving of research and practice and the cooperation of academia and industry. The reader should refer to Solheim et al. (2005a, b); Kvalstad et al. (2005a, b); Kvalstad (2007); Nadim et al. (2005) and the special issue of Marine and Petroleum Geology (2005) for a complete account of the slide and a summary of the studies by the parties involved.

The design questions that needed to be answered were: (1) Can a new large slide, capable of generating a tsunami, occur again, either due to natural processes or through the activities required for the exploitation of the field; and (2) Can smaller
slides be triggered on the steep slopes created by the Storegga slide, and if so, would they endanger the planned offshore installations to recover the gas resources?

Based on the studies in the SEABED project, the triggering and sliding mechanics used the observed morphology and the geotechnical characteristics of the sediments. The average slope angle was only $0.6 - 0.7^\circ$. The geotechnical properties indicated shear strengths far above those required to explain a failure. However, the geophysical observations, especially seismic reflections profiles in the upper parts of the slide scar, provided strong indications that the failure developed retrogressively (Fig. 2.10). Using the retrogressive slide model as working hypothesis, several scenarios of sources of excess pore pressures were considered, including (1) earthquake-induced shear strain generating excess pore pressures, (2) melting of gas hydrates releasing methane gas and water, (3) shear strain-induced contraction with pore pressure generation and strain-softening and (4) rapid deposition. The studies concluded that the most likely trigger was an earthquake destabilizing a locally steep slope in the lower part of the present slide scar. The retrogressive process continued up-slope until conditions improved with stronger layers, related to the consolidation of the shelf sediments during glacial times. Once the instability started, excess pore pressures already generated during rapid sedimentation under the last glaciation were an important contribution to the large slope failure (Bryn et al. 2005).

Excess pore pressures still exist at the site, as demonstrated by in situ monitoring (Strout and Tjelta 2005). The excess pore pressures recorded in several locations and at several stratigraphic levels support the depositional role in the Storegga failure proposed by Bryn et al. (2005).

Seismic studies by Bungum et al. (2005) showed that strong, isostatically induced earthquakes along the mapped faults at the site and stress transfer-induced earthquakes had occurred earlier. They also suggested that multiple strong earthquakes with extended duration most likely occurred and could be the potential trigger for the Storegga slope instability.

![Fig. 2.10](image) Bathymetry and seismic profiles in the upper headwall at Ormen Lange and interpreted morphology of slide (Kvalstad et al. 2005a)
The tsunami generating potential of submarine slides is today widely recognized. Tsunami studies indicate that the field observations of tsunami run-up fitted will be the retrogressive slide model with velocity of 25–30 m/s, and short time lags of 15–20 s between individual slide blocks (Bondevik et al. 2005). The slide mass involved in the tsunami generation modelled was 2400 km$^3$.

Figure 2.11 illustrates the hemipelagic deposition of fine-grained sediments in the area of the Storegga slide. One of the pre-conditioning factors for sliding at Storegga was the presence of “weak layers”. The stratigraphy and lateral extent of slide-prone deposits (i.e. the contourite drifts in Fig. 2.11) created “weaker” layers that increased the susceptibility of the slope to failure under earthquake loading. The contourites were controlled by the seabed topography and current direction. Deposition of soft marine clays is in fact still ongoing in the slide area.

Figure 2.12 presents a schematic illustration to explain the sedimentation process leading to failure, which supports the hypothesis that major slides have occurred in the Storegga area on a semi-regular basis, related to the glacial/interglacial cyclicity.

The bottom illustration in Fig. 2.12 (denoted 1) gives the last interglacial with deposition of soft marine clays. The middle illustration (denoted 2) presents the last glacial maximum (LGM) with the ice at the shelf edge and deposition of glacial sediments. The top illustration (denoted 3) presents the topography after the Storegga slide. Dating (BP, before present) is given for each illustration. The illustration denoted 3 also shows two older slide scars that were filled with marine clays. The slip planes were found in seismically stratified units of hemipelagic clays.

Fig. 2.11  Location of the main contouritic drifts (in yellow) (Bryn et al. 2005)
deposits and the thick infill of stratified sediments indicate a late glacial to early interglacial occurrence of slides (Bryn et al. 2005).

The soft fine-grained hemipelagic deposits were rapidly loaded by coarser glacial deposits during the short glaciations period. Excess pore pressures were a destabilizing factor. The hypothesis of strong earthquake shaking was retained to start the underwater slide. After the earthquake initiated the movement, the slide moved retrogressively by back-stepping up the slope where the pore pressures were already high. The mass movement was further facilitated by the release of support at the toe.

The stability of the present situation at Ormen Lange was evaluated by Kvalstad et al. (2005b). The conclusion was that an extremely strong earthquake would be the only realistic triggering mechanism for new submarine slides in the area. The annual probability of third-party damage was also investigated and found to be extremely low (Nadim et al. 2005). The project team therefore concluded that developing the Ormen Lange gas field could be done safely.

Fig. 2.12 Schematic of the deposition and sliding processes (green glacial sediments; red slide deposits; blue marine sediments) (Bryn et al. 2005)
In general, the geohazards assessment should include the components in Fig. 2.13, incorporating in each assessment the uncertainties in the parameters (represented in Fig. 2.13 by probability distribution functions in red).

2.3.1.1 The Role of the Expert in Forensic Engineering

Day (2011) presented a Recommended Practice for design professionals engaged as experts in the resolution of construction industry disputes prepared by the ASFE (1993). The 13-step guideline is summarized in Plate 2.1.

The author finds that the 13 guidelines are not specific to forensic engineering, but represents a good practice in all parts of geotechnical engineering. They speak of:

- avoiding conflicts of interest, placing integrity first;
- displaying professional demeanour, including respecting confidentiality;
- remaining within one’s area of expertise;
- studying the facts and data in a thorough fashion and listening to other experts’ opinions;
- striving for quality in all steps of the work;
- presenting findings in a concise and clear manner.

Any geotechnical engineering project, not only forensic engineering, needs to follow these guidelines.
Nevertheless, forensic engineering is complex. Engineers typically work in collaboration where they challenge each other to arrive at the best engineered solution or design possible. In litigation, collaboration is replaced by criticism, sometimes of well-supported professional opinions. Forensic engineering must therefore ally the best of science with the art of conflict resolution, all within a frame of important economical consequences for one of several parties. The requirements of forensic engineering are so demanding that not all geotechnical individuals can deliver good testimony. Specific qualities are required of forensic geotechnical engineers, including effective public speaking, a quick and logical mind and repartee, and exceptional pedagogical qualities, in addition to a thorough understanding of the subject of litigation.

An important responsibility is therefore to know when to say no to a request of expert opinion in the case of litigation.

### 2.4 Summary and Conclusions

The practice of forensic geotechnical engineering is the application of geotechnical engineering to answer questions of interest in the context of litigation, where the engineering and legal professions are brought together to resolve the conflict on responsibility for a failure. The geotechnical engineer must apply science and engineering within the rules of the legal system, in order to present effective arguments.
Practitioners are naturally drawn to failures as they provide opportunities to verify calculation procedures, and increasing judgment and understanding on how and why the application of existing knowledge failed to achieve the intended result. The practice of forensic engineering is therefore one of the most interesting and most challenging tasks for a geotechnical engineer.

Forensic engineering is however paradoxical. Engineers typically work in collaboration where they challenge each other to conclude with the best engineered solution possible. In litigation, collaboration is replaced by criticism, sometimes of well-grounded professional opinions. Forensic engineering must therefore ally the best of science with the art of conflict resolution, all within a frame of important economical consequences for one of several parties.

When an expert presents its opinion on the cause or responsibility for a failure, the opinion must be well founded, and most importantly, presented in a way that the judge or jury can understand the technical issues in dispute (Lucia 2012). Simple demonstrations have proven to be very effective to explain physical and/or mechanical behaviour. Lucia (2012), based on 25 years of forensic geotechnical engineering experience, stated that while jurors and judges do their best to sort out the issues, the results can often be confusing. He suggested that settlement of the dispute prior to proceeding to trial is almost always the preferable outcome. In any case, a thoughtful, high quality forensic technical investigation consistent with good science and engineering combined with an ability to clearly present the matters being disputed will always aid in the settlement of the dispute or the outcome of a trial.

The requirements of forensic engineering are so demanding that not all geotechnical individuals should go into forensic engineering, and that specific qualities are required of forensic geotechnical engineers, including effective public elocution, a quick and logical mind and repartee, and exceptional pedagogical qualities, in addition to a thorough understanding of the subject of litigation.

Acknowledgments The author is thankful to her many colleagues at NGI and from our research partners for their contribution to the case studies. Part of the work was funded by the project SEABED through the Norwegian Deepwater Programme and by NGI’s Centre of Excellence “The International Centre for Geohazards”. The author acknowledges in particular the key contributions made by Maarten Vanneste, Jean Sébastien L’Heureux, Carl-Fredrik Forsberg and Tore Kvalstad from NGI, Mark E. Vardy from Southampton University, Oddvar Longva and Shyam Chand from the Geological Survey of Norway, Hafli Haflidason and Jo Brendryen from the University of Bergen and Alois Steiner from MARUM, in Bremerhaven.

References

ASFE (1993) Recommended practice for design professionals engaged as experts in the resolution of construction industry disputes. ASFE (association of engineering firms practicing in the geosciences). Silver Springs, MD, 8 pp


Forensic Geotechnical Engineering
Rao, V.V.S.; Sivakumar Babu, G.L. (Eds.)
2016, XVI, 552 p. 411 illus., Hardcover
ISBN: 978-81-322-2376-4