ISSMGE TIME CAPSULE PROJECT (TCP)

TC 302 – Forensic Geotechnical Engineering

Failures are not all bad; in fact, they can be more useful to engineers than successes if they are thoroughly studied in order to answer important questions such as how to improve our performance and what patterns of erroneous thinking and generalizations we should avoid. In fact, studying case histories of failures and learning from the mistakes of others is the most fruitful source of lessons in engineering judgment.

Hammurabi, the great Babylonian king, had one of the earliest recorded legal codes dealing with construction. His construction legal code was straightforward: The contractor will be killed if he builds a house and it collapses, killing the owner. If the owner's son is killed, the contractor's son will be as well.

Modern legal codes have evolved from Hammurabi's simple code and are more complex. FitzSimons (1986) describes the 1782 case of Folkes versus Chadd as a major milestone in the evolution of modern civil law and the application of forensic engineering. Folkes was a landowner who constructed a dike around his low-lying property. Chadd, a trustee of a nearby harbour, claimed that the dike had eroded and silted up the harbour. Folkes filed a lawsuit after Chadd obtained an order to have the dike removed. During the trial, well-known engineer John Smeaton testified that, in his opinion, the dike was not to blame for the harbour's silting up. The court ruled that Smeaton's opinion could be taken into account and stated:

"Only men like Mr. Smeaton can make a decision on this. As a result, we believe that his decision, based on facts, was very appropriate evidence."

Forensic engineers could then be used to judge the facts and render opinions in a court of law.

Greenspan et al. (1989) presented the ASCE guidelines for a failure investigation and emphasised on the forensic engineer's qualifications. As stated in this publication, a forensic engineer must possess a number of general characteristics. The first and most important requirement is a thorough understanding of the subject under investigation. This expert knowledge could have been obtained through advanced education and years of practise. If the subject under investigation is not within the forensic engineer's area of expertise, the assignment must be declined. Another important characteristic is that the forensic engineer must be objective regarding the cause of the problem and who is responsible for the damaged or deteriorated structure/infrastructure. The forensic engineer must reach a final conclusion based on sound engineering principles and evidence gathered during the investigation.

Forensics in the geo-domain covers a wide range of topics, with a particular emphasis on geotechnical field. Forensic geotechnical engineering (FGE) is a new discipline that deals with investigations of soil-interaction-related failures of engineered facilities or structures. A practising geotechnical engineer cannot offer services without the fear of being sued. Geotechnical engineers with experience in the legal system are hired to investigate such failures.

Why forensic geotechnical engineering?

Geotechnical failures can be catastrophic/ultimate state failures or serviceability limit state failures, in which the unacceptable disparity between the expected and observed failure comes in the form of cracks, distress, loss of contact, and so on. The following reasons may be responsible for failures that can be considered by forensic geotechnical engineering.

a. Problems caused by expansive and/or collapsible soils
b. Settlement of shallow and deep compacted fills
c. Pavement and embankment failures
d. Slope protection failures
e. Foundation and excavation failures
f. Underground pipeline and tunnel failures
g. Site runoff and drainage
h. Soil erosion
i. Liquefaction and sand boiling
j. Slope stability and landslides
k. Geoenvironmental problems

In most cases, forensic geotechnical engineers are hired to look into such failures. "What happened?" and "Why did it happen?" are usually the first two questions posed to the forensic engineer. Of course, this is followed by, "How can it be fixed?" and, all too often, "Who's fault is it?" and "Who is going to pay?"

FGE trains civil engineers to think, read, speak, and analyse like lawyers. Furthermore, it familiarises him/her with the legal system so that he/she is better able to understand and deal with legal issues because he/she has to work closely with prevailing statutes and regulations, and may become involved in litigation, or may serve as an expert witness.

Studies on Forensic Geotechnical Engineering from 1953 to 1999

The forensic procedure evaluates how the structure functioned in the past. In this regard, the following steps are required

1. collection of data
2. distress characterisation
3. development of failure hypothesis
4. diagnostic tests
5. back analysis
6. reliability aspects
7. technical shortcomings
8. legal issues
9. observational method of performance evaluation.

Peck and Bryant (1953) investigated the failure of Transcona grain elevator failure. In 1913, a grain elevator near Winnipeg, Canada experienced a bearing capacity failure during its first loading. The structure consisted of reinforced concrete work-house and an adjoining bin-house. Peck and Bryant mentioned that bin-house experienced a settlement on October 18, 1913 after 875,000 bushels of wheat had been stored in the elevator. Within an hour the settlement had uniformly increased to about one foot. This was followed by 26°53’ tilt from vertical. They stated that the elevator was underlain by uniform clay deposits from the wash borings. The undrained triaxial tests revealed that the confining pressures appear to have had no effect on the compressive strength, implying that the soil would behave as if $\phi = 0$, with cohesion or shear strength c equal to one-half the compressive strength. The time dependence of the porewater pressure generation was investigated in order to determine whether catastrophic failure could have been avoided by using staged loading (Blatz and Skaftfeld 2003). They observed that using a design factor of safety of 1.2, the bins could have been loaded to approximately 60% of their capacity over a one-month period before allowing approximately one month for dissipation of excess pore water pressures.

Terracina (1962) pointed two major causes of instability of the Pisa tower. The causes include (a) the difference in soil consistency on the sides of an east-west axial plane, (b) the inequality of the contact pressure as a consequence of the induced eccentricity of the load. The 56-m high “leaning tower” of Pisa was built in three phases between 1173 and 1370 on the alluvial sediments of the river Arno, central west Italy. Although the tower deviated from vertically early on, the towers continued tilt has raised concerns about its safety.

Leonards (1982) defined failure as an unacceptable difference between expected and observed performance. Examples of soft clay cut slope failures, soft clay embankment failures, and large pile foundation failures during proof loading were discussed. Leonards proposed the establishment of a National Center for Investigating Civil Engineering Failures in order to develop rewarding methodologies for investigating failures, to make lessons learned cumulative and accessible to the profession, and to provide focal points for rewarding research with the sole aim of significantly reducing the frequency of unexpected failures.

Ehlig (1986) examined the Portuguese Bend landslide and presented the landslide mechanics as well as a strategic plan to stabilise the landslide. Seed et al. (1990) presented the key geotechnical aspects of the 1989 Loma Prieta earthquake. They concluded that the three most important geotechnical factors were: (1) site effects on local dynamic response, (2) soil liquefaction, and (3) slope stability issues. In addition, Seed et al observed that one of the most likely outcomes of this tragic earthquake will be a greater awareness of the potential importance of these factors within the global earthquake engineering community.

Despite our current very advanced analytical capabilities, our ability to predict actual field behaviour is woefully inadequate in many cases (Mitchell, 1986). Mitchell described four cases to illustrate one of the reasons why actual and predicted performance can sometimes be so far apart - a failure to understand how a soil might respond to changing conditions over time. The four cases are as follows: (1) the ageing of quick clay after sampling, in which the remoulded strength increases in samples kept at constant water content; (2) time effects in freshly densified or deposited sand, in which natural sand deposits can lose strength if disturbed but regain strength over time periods ranging from weeks to months; and (3) apparently sound lime-stabilized soil that swells and disintegrates a few years after construction, and (4) the failure of excess pore pressures to dissipate as predicted during soft clay consolidation.

Belloni and Stefani (1987) discussed about the instrumentation, past experience and the modern approaches to the Vajont slide. They concluded that a combination of a significant (no less than 100 m) reduction of the maximum reservoir level and an expensive tunnel-based drainage scheme of the failure surface could have achieved a sufficiently low risk of failure.

Nonveiller (1987) investigated the stability of Vajont reservoir slope and discussed about the cases of reservoir slope failure. Hambly (1990) examined and discussed about the overturning instability in detail. Guerra (1992) investigated the causes for soil deformations at the metropolitan Cathedral in Mexico City. Guerra also provided the solution to mitigate the deformations.

Sowers (1993) explained the human factors that are involved in the civil and geotechnical engineering failures. The author investigated 500 failures and discovered that the majority of failures (58%) are associated with design, 38% with construction, and 4% with operation. Human shortcomings account for 88% of the total, which can be reduced by acknowledging professional limitations, continuing education, modifying design and construction systems, and resisting the unbalanced pressure that stymies good engineering.

Focht (1994) focused on the broad factors critical to the prediction process that govern the accuracy of predictions of completed structures' geotechnical performance. He emphasized the value of judgement (questioning each aspect of the prediction process) and intuition in the development of geotechnical predictions. Some types of predictions are identified for which success is expected to be limited. He concluded with a short discussion of how to develop good judgement. Burland et al. (1998) presented the temporary remedial measures that were taken to stabilize the Leaning Tower of Pisa". They mentioned that temporary plastic coated steel tendons were provided to support the cracked walls without creating any noticeable visual impact. They also pointed that permanent works to reduce the tilt were planned, which include the drilling of a series of boreholes through which small amounts of soil can be removed. Burland et al. (2020) provided the subsoil conditions of the tower (Pisa Tower) in three layers. They pointed that the tower inclined at 0.6^{o} southward in 1278 and the increased to about 1.6^{o} in the next 90 years. Further they mentioned that the inclination of the tower of Tower was about 4.9^{o} in 1817. The analyses (Burland and Potts, 1994) using a finite-element model based on a nonlinear elastic isotropically hardening plastic constitutive model of the subsoil revealed that a maximum load of 14 MN could have been safely applied. Burland et al. (2020) stated that the counterweight induced a change of inclination of 33 arc seconds by February 1994; by the end of July, it had increased to 48 arc seconds and eventually to 52 arc seconds. On February 1994, the average additional settlement of the Tower relative to the surrounding ground was about 2.5 mm. With this in mind, an alternative counterweight system was devised (Viggiani and Squeglia, 2005), based on the use of ten ground anchors consisting of steel cables cemented into the lower sands at a depth of 45 m. Finally they concluded that underexcavation found to be effective out of all other ground improvements methods including micropiles.

The factors that contribute to claims of changed subsurface conditions in large-construction contracts are investigated by Gould (1995). He discussed methods for resolving the associated disputes and describes a number of cases to illustrate the relevant issues. These cases are primarily concerned with mined tunnels, which are the most severely impacted by the unexpected. Gould tried to summarise the special requirements for preparing geotechnical information for construction and to recommend procedures for avoiding claims or resolving them in an equitable manner. Vermeer (1997) analysed the leaning tower of St. Moritz in PLAXIS and discussed about the various reasons of the failure.

Rampello and Callisto (1998) conducted a study on the subsoil of the tower of Pisa based on the results obtained from standard and high quality samples. Gilbert et al. (1998)

investigated the failure of Kettleman Hills MSW slope failure in the light of reliability. They concluded that neither the peak nor the residual strength was not likely causes of failure in this case. Akai and Tanaka (1999) discussed the problems associated with the construction of Kansai International Airport (KIA). Akai and Tanaka examined the settlement behavior of seabed soils consisting of several layers of Pleistocene clays, and found that these clays exhibit typical characteristics of aged clay. Soriano and Sanchez (1999) presented the causes for the settlements of railroad high embankments.

Studies on Forensic Geotechnical Engineering from 2000 to 2021

Despite the fact that several authors have been conducting forensic analysis in geotechnical engineering for many decades, the approach to dealing with failures remains consistent. The step-by-step procedure for dealing with forensic analysis remains unchanged. However, there has been significant advancement in technology and the testing methods used in the analysis. Many geotechnical problems have seen significant improvements with increased computational efficiency in recent days, allowing for back analysis. A large amount of data is available for the stability analysis of the geotechnical infrastructure.

The advancement in the forensic geotechnical engineering includes the following

1. *Collection of data*

Geographical information system (GIS) maps and satellite imageries, GPS receivers, laser scanners and LIDAR systems, robotic total stations, digital automatic levels etc.

2. *Distress characterization*

Unmanned aerial vehicles (drones), the use of sensor based technologies, and fibre optic sensors.

3. *Diagnostic tests and methods*

Cyclic simple shear testing, dilatometer and pressure meter testing, inclinometer tests, multichannel analysis of surface waves (MASW), ground penetrating radar (GPR) testing, and scaled model based centrifuge tests that capture essential failure mechanisms.

4. *Back Analysis*

Back analyses are required to provide technical evidence to support or refute hypotheses about the causes of failures and to establish failure scenarios. The back analysis method is popular because they are relatively easy to perform, having the site characterisation data from the original design.

Reliability Aspects

An important factor in the posterior assessment of the geotechnical design lies in the appropriate recognition of the existence and magnitude of uncertainty in the design phase. It is feasible to determine if the factor of safety is "adequate" for a given expected degree of reliability based on prior experience and a first-order estimate of the likely coefficient of variation (COV) of the factor of safety based on forensic evidence.

Duncan (2000) analysed the San Francisco slope, consolidation settlement, and settlement of footings on sands. Duncan concluded that the slope was designed for a probability of failure less than 18%, whereas from the analysis it was found to be 18% which triggered the failure. Duncan further stated that the coefficient of variation for during-consolidation and ultimate settlements will in general not be the same. Duncan proposed that probability of failure should not be viewed as a replacement for factor of safety, but as a supplement and computing both factor of safety and probability of failure is better than computing either one alone. Davies (2000) discussed about the possibilities of the mine tailing dams and the lessons learned from them. Sassa and Sekiguchi (2001) analysed wave induced liquefaction of sand beds. Cummings and Kenton (2004) carried out the investigation of case studies of failures in geotechnical engineering. The failure studies include collapse of the trench, rainfall induced slope failure, earthquake induced landslide, and failure of an earth dam. They identified the causes for the reported failures and concluded that failures are caused by human errors that allow marginally stable or unstable conditions to exist through substandard investigations, dishonesty and deceit, approval of substandard reports by reviewing agencies, and political influence. Delage et al. (2005) highlighted various geotechnical problems associated with loess deposits due to moisture changes in Northern France. Gens and Alonso (2006) presented the stability conditions and failure mechanism of Aznalcollar dam. Gens and Alonso observed that the homogeneous nature and very low permeability of the foundation clay and the natural state of the clay, probably affected by some initial damage, and reduced the available strength along bedding planes. Saxena (2008) used forensic analysis to determine the causes of building foundation settlement and slope failure.

TC-302 conducted an international seminar on forensic geotechnical engineering in order to raise awareness of the subject. The first international symposium on forensic approaches to geohazard problem analysis was held at IIT Bombay in 2010. Several authors at this conference emphasised the importance of forensic geotechnical analysis and presented case studies on geotechnical infrastructure failures. Dave (2010) provided the forensic aspects of professional services as geotechnical consultants. Dave emphasised the legal aspects of professional consulting and explained relevant aspects of construction law as they relate to the discussion of damage theories and design liability. Prakash and Puri (2010) presented the developments of liquefaction analysis from observations during earthquake. Prakash and Puri noted that silts and low plasticity clays also liquefy based on the observations from Tangshan and other earthquakes. Iwasaki and Haruna (2010) presented a case study of floor heaving of condominium RC-building with seven stories. They found that the cause was due to the use of steel slag mixed in filled soil under the structure. They further observed from chemical analysis that free lime in the steel slag was identified as the primary cause of the problem.

Xu and Zhang (2010) diagnosed the causes of geotechnical failures using Bayesian networks. Rao and Sargunan (2010) analysed several geotechnical failures and presented the technical vulnerabilities in geotechnical failures for Indian scenario. Ghosh (2010) emphasised the effect of cloud burst on vulnerable establishments in Leh. Ghosh highlighted some of the infrastructure damages due to August 6th 2010 mudslide. Sarma (2010) presented an innovative technique using continuous energy logging (CEL) for forensic analysis of failure of foundation.

Phoon et al. (2010) illustrated a statistical method for the objective assessment of responsibility in geotechnical design from a forensic perspective. Phoon et al observe that if the safety factor is deemed to be sufficient, the observed failure is unlikely to be explained by underlying geotechnical variations, and attention could be productively focused on other causes such as geologic surprises, gross human errors, etc. Puzrin et al. (2010) discussed about the various factors that are responsible for the failure of transcona grain elevator (Canada), caisson failure induced by liquefaction (Barcelona harbour, Spain), leaning instability: the tower of Pisa (Italy), excessive settlement of Kansai international airport (Japan), Nicoll highway (Singapore), Borras square (Spain), and Floresta tunnel (Spain). Despite the emphasis on simplicity, they provided deep insights into the cases studied. Alonso et al. (2010) emphasised the causes of failure of Brattas-St. Maritz landslide (switzerland), Vaiont landslide (Italy), road embankment (Spain), and sliding failure of Aznalcollar dam (Spain). Alonso et al. also presented a short description of the changes in the original design and the mitigation measures which could have prevented the failure.

Green et al. (2011) highlighted the geotechnical aspects of failures at Port-au-Prince Seaport during the 12 January 2010 Haiti earthquake. They reported that the Haiti earthquake caused ground failures in calcareous-sand artificial fills at the seaport, including liquefaction, lateral spreads, differential settlements, and collapse of the pile-supported wharf and pier. The site characterization includes geotechnical borings, hand-auger borings, standard penetration tests, and dynamic cone penetration tests. Baars (2011) presented several examples of geotechnical failures. The failures include water defense system of New Orleans, Singapore metro tunnel, train station building pit, subsidence along underground train station at Amsterdam, Leaking tram tunnel at Den Hague, Garage building pits at Rotterdam and Middleburg, Peat dike failure at Wilnis, and retaining wall of building pit. Baars concluded that the biggest risk parameter in geotechnical design is therefore not the spread of load or strength parameters, but by far the existence and quality of the internal project auditing and the external project design control. Koerner and Koerner (2011) discussed the importance of drainage control for the geosynthetic reinforced mechanically stabilized earth walls through various MSE wall failures. They analysed 82 case studies and found that 68% of them were failed due to improper drainage control in MSE walls. They mentioned that internal drainage issues within the reinforced soil mass is about 46% and external drainage issues around the soil mass is 22%.

Day (2011) presented the forensic geotechnical and foundation engineering. He presented a detailed procedure for forensic analysis in geotechnical and foundation engineering along with the case studies and examples. Liu et al. (2012) discussed the lessons learned from three failures on a high steep geogrid-reinforced slopes. They observed that the first slope failures was occurred in 1994 at Taiwan due to heavy rainfall. They found that the interface of laterite gravel and clay created a detrimental bedding plane and its shear strength was reduced by the infiltration. The second failure, which occurred in 1999, was caused by a powerful earthquake. The overstress began near the clay layer, retained zone, and reinforced zone. The overstressed zone dissipated into a retained natural slope, resulting in the formation of a mass slide. The third failure occurred in 2004 during a heavy rainstorm when abundant rainfall infiltrated the reinforced slope. Because no sub drainage system was designed, the obstructed infiltration caused by the impermeable clay and fine contents in the backfills began to generate significant transient water pressure, causing slope failure behind the reinforced zone.

In 2013, TC-302 hosted an international seminar on forensic geotechnical engineering at IISc Bangalore. Many authors presented innovative methodologies used in forensic geotechnical engineering at this conference. In forensic geotechnical engineering, several authors emphasised the importance of uncertainty and reliability, back analysis, instrumentation, and monitoring.

Rogers and Hasselmann (2013) investigated the failure of St. Francis dam near southern California. The failure of the St. Francis dam was caused by a number of siting and design flaws, many of which were not unique to the early 1920s, according to the authors. Bosela et al. (2014) investigated various case studies on foundation failures, embankment, dam, and slope failures, and geo-environmental failures. They discussed the causes of failures of the historic structures like Tower of Pisa, Transcona grain elevator (1913), Fargo grain elevator (1956), La Playa Guatemala earthquake (1976), Schoharie Creek bridge (1987). Furthermore, they presented about the possible failures of St. Francis dam (1928), Teton dam (1976), Carsington embankment (1984) and Kettleman Hills waste landfill (1988).

Endicott (2015) presented the lessons that were learnt due to the design and construction of excavations in the urban areas. He discussed about the causes of failures of Queen's road (Hong Kong), Taegu metro (South Korea), San Paolo metro, Hang Zhou metro, Nicoll highway collapse (Singapore). Endicott mentioned that on the 20th of April 2004, an 80 m long section of excavation, 30 m deep, completely collapsed during the construction of Contract C824 of the Circle Line in Singapore. The resulting crater reached depths of up to 15 metres and had a diameter of more than 100 metres. Six lanes of the nearby Nicoll Highway sank by up to 13 metres. Four workers in the construction industry were killed. Endicott reported that the Nicoll highway failure is attributed to improper use of computer program, and inadequately designed walls. Furthermore, Endicott stated that the level of supervision of the works was deemed insufficient in the case of Queen's road collapse. Endicott also mentioned that the Taegu metro collapse was caused by the presence of unidentified strata of sands and gravels, which were subjected to a rapid increase in ground water level to an extent that had not been planned for. Moreover Endicott pointed that the likely cause of San Paolo metro failure was fractured rock located above the station, as well as a lack of sufficient supports to the roof and side walls of the excavation for station.

Ering et al. (2015) and Ering and Babu (2016) performed a probabilistic back analysis of rainfall triggered Malin landslide in India. A devastating landslide in western India on July 30, 2014, buried a village called Malin and killed approximately 160 people. They performed a coupled transient seepage and probabilistic back analysis to find the possible causes of the landslide. They observed that high intensity and short duration of the rainfall infiltration caused the slope failure. In addition, they found that reduction in matric suction decreases the shear strength of soil and increases the positive pore water pressure.

TC-302 organized an international conference on forensic geotechnical engineering at IISc Bangalore in 2016. Several authors discussed the cutting edge research that is taking place throughout the world in forensic geotechnical engineering at this conference. The importance of field instrumentation and monitoring, and reliability analysis was emphasised by the authors.

Agaiby and Ahmed (2016) presented the possible causes of failure of St. Francis dam, California, USA. St. Francis dam was a 57m high, 213 m long, curved concrete gravity dam built for the City of Los Angeles in 1924-1926. It stored 47 million m3 of water. Just before midnight of March 12, 1928, the dam collapsed and the resulting flood took the lives of 431 people. The possible reasons for the failure were piping instability behind the dam, instability in overturning due to the increase in the height of the dam without increase in base width.

Further Agaiby and Ahmed stated that the number of failure could be reduced by conducting proper and adequate geotechnical site investigations, using more flexible/conceptual designs in conjunction with the Observational Method (as opposed to rigid, fully-engineered designs), and employing strict site supervision and quality control.

Poulos (2016) sets out a framework for investigating the possible causes of foundation failures in a systematic manner. He presented an example to illustrate the application of the approach developed to a case involving failure of a piled foundation. Lacasse (2016) highlighted the role of geotechnical engineer as a forensic expert in particular in investigating damage and failure, evaluating the hazards and consequences, developing repair recommendations and preparing reports. Rao (2016) provided overall view of the procedures to be adopted in forensic analysis.

Xu and Zhang (2016) used Bayesian networks to diagnose geotechnical failure causes. They used Bayesian networks to diagnose the distressed dam by systematically combining prior information from the database and project-specific evidence. Authors concluded that key distress factors for the dam can be identified and appropriate remedial measures can be suggested based on the results of the diagnosis. Babu and Singh (2016) emphasised the use of back analyses to analyse the failures that occur frequently in geotechnical engineering. Furthermore, the importance of in situ conditions, investigations, techniques, problem complexity in terms of three-dimensional effects, and so on is emphasised in the field of forensic studies in geotechnical engineering.

Iwasaki (2016) explained the technical basic knowledge of two new innovative instruments in geotechnical engineering. He explained briefly about the carrier phase tracking GPS and BOTDR (Brillouin Optical Fiber Reflectometer). The former one is used to for measuring displacement between reference GPS receiver and target GPS receiver with a high accuracy of displacement of 2–5 mm. Whereas, the later provides the information regarding strain and temperature. Madabhushi (2016) demonstrated the utility of dynamic centrifuge modelling in deciphering pile behaviour through observation of failure mechanisms is demonstrated. Furthermore, he proposed that dynamic centrifuge modelling is a valuable tool for forensic engineering in the field of geotechnical earthquake engineering.

Koerner and Koerner (2018) performed the statistical analysis on the number of failures and mode of failures of RE walls. They have taken 302 case studies around the world and reported that 245 failures were due to the poor and moderate compaction. Furthermore, it is noted that 232 failures were due to the usage of silt or clayey soil as a back fill material in the reinforced zone. Boiero (2019) presented the failures associated with soil-structure interaction problems. Finno (2020) discussed the technical and non-technical causes of excavation support failures. He concluded that the design and construction are interrelated and most of the failures are due to redundancy in design and construction. Bonaparte (2020) reviewed several MSW slope failures from the 1980s and 1990s and presented the lessons learned during that period. Following a review of several more recent waste fill failures, it is concluded that 20–30 years after the earlier failures, facility operators and design engineers are relearning the earlier lessons, as well as new lessons related to evolving waste streams and operating practises.

Rowe (2020) highlighted the influence of human factors in engineering failures. He emphasised some common problems with several examples. According to Rowe, the human factors include; poor decisions, poor communications, do it right or don't do it all, excessive focus cost/schedule, failure to adequately investigate, failure to consult or listen, wishful thinking, failure to check or consider, watch for the poisoned apple, knee-jerk response, etc. Iwasaki (2020) presented about the capability of the geotechnical engineer to prevent the geo-disaster through two case studies. He discussed about the lack of the capability of reading of the monitored results and the local character of the geotechnical condition. Further, he highlighted some additional capabilities and specified regions for the work. Shin (2020) discussed about the safety measures that need to be taken for the underground structures. He emphasised the education and training program, fusion technology incorporated big data, and smart technology for the prediction of the ground movement in advance. Shin presented about the GIS based informative management for prevention and reduction of geo-disasters. Hou (2020) highlighted several geotechnical incidents that influenced the geotechnical landscape in Singapore. Collin et al. (2020) investigated the reinforced slope failure at the Yeager airport near Charleston, West Virginia. They conducted 2-D and 3-D limit equilibrium analysis and 3-D permanent deformation analysis on the reinforced slope. They confirmed from finite-difference deformation analyses that the reinforced soil slope's strength decreased along the soil–rock interface over its 8-year service life due to deformations caused by applied shear stresses and available groundwater. They further concluded that the failure surface propagated from below the reinforced zone near the slope toe, behind the geogrids in the lower portion of the slope, and through the geogrids in the upper portion of the slope.

Li et al. (2021) presented their findings from a forensic geotechnical investigation of the Skjeggestad quick clay landslide in Norway. They examined the evidence from the soil investigation, available topographic data, in-situ observations, eyewitness statements, and drone photographs. They used these evidences to reconstruct the most likely cause of the landslide. Puppala (2021) discussed about the infrastructure distress recorded from the natural and manufactured expansive soils. The failures includes MSE wall movements, pavement cracking due to differential heaving, slope failures from embankment soil cracking, and home masonry cracking from underlying soil movements. Puppala summarized the recent innovations for better health monitoring and management of civil infrastructure built on expansive soils using unmanned aerial vehicle platforms and visualization tools, which will be valuable for validating the application of new materials, designs, and construction processes.

TC-302 conducted an international webinar on forensic geotechnical engineering in in 2020. The speakers at conference speakers discussed the role and significance of forensic geotechnical engineering. The new geotechnical engineering innovations in instrumentation and monitoring were highlighted.

Further work in the committee

In future the committee is planning to collect the forensic geotechnical engineering database.

The failure case history database consists the following:

1. ***The value***
   The database of failure case histories are important to enhance knowledge, research and awareness purposes (e.g. PEER reports, USA and EEFIT reports, UK form a good database of failures due to powerful earthquakes).
   The enhanced knowledge would help to improve the industry practise. The research tool is important to investigate the root causes of failure and to validate

theories and models. Awareness about the failure case studies may educate the students and practitioners.

2. ***Sources of data***

   The sources of data may be from any of the following technical and/or non technical sources.

   They may be from press releases, newspaper articles, TV news broadcasts, forensic investigation reports, scientific conference papers, Journal paper, Books/Book chapters.

3. ***Development***

   The database shall be structured in a way to allow contribution of all kinds of acceptable data

   *Criteria for classification and acceptance of cases shall be provided (**TC 302 development committee**). A technology provider will set up the platform and host the data. Users will contribute freely material (contributions may be acknowledged). Control over copyright or confidentiality restrictions. University (educational) programs may contribute to meta data development.*

4. ***Geotechnical Failure cases***

The geotechnical failure cases may consists the following.

a. References

   The references may be from any of the following

   Press releases, news articles, internet links, photographs, video, documentary films, journals, book chapters, and technical reports.

b. Data

   The failure case studies data can be in the form of

   Http links, pdf files, geospatial, geological, boreholes, accelerograms, rainfall data, suction measurements, and modelling results.

c. Meta-Data

   Meta data can in the form of

   Structural category (dams, retaining walls, landslides, and foundation etc.),

   I. *Ground category (Unsaturated soil, clay, sand, rock, etc.),*
   II. *Loading category (Groundwater, Earthquake, wave loading, etc.),*
   III. *Failure root cause (Design, materials, construction, overloaded, unmaintained, etc.),*
   IV. *Consequences (fatalities, monetary losses, downtime, reputation, etc.), and*
   V. *Mitigation and aftermath (Strengthened, Rebuild, Abandoned, Code upgrade, QA/QC upgrade, etc.).*

The forensic geotechnical engineering is not the collection of cases of geotechnical failure. The failures need to be discussed with legal aspects.

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