A Multi-faceted Approach to Geotechnical Engineering Education

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ABSTRACT: Central to effective student learning is engagement. This paper presents a student-centred approach to enhance engagement and, hence, improve learning outcomes in geo-engineering education. The approach incorporates a variety of facets or tools, which include: demonstration models; videos and documentaries; e-learning; and case studies incorporating geotechnical failures. These aids are particularly effective when used in combination with the traditional forms of lectures, tutorials, experimental classes and design projects. The paper includes details of each of these learning tools and the contribution each makes to improving student engagement and learning.

1 INTRODUCTION

It is widely accepted that a significant key to effective student learning is engagement (Bowen, 2005; Carini et al., 2006; Bryson & Hand, 2007). The traditional forms of geo-engineering instruction, such as formal lectures, tutorials, experimental practical classes and design sessions, remain as relevant today as they ever have in the past. However, in general, students of today, as part of their pre-tertiary education, have been exposed to a much richer variety of pedagogical methodologies and media than the traditional forms of instruction mentioned above. As a result, it is now a greater challenge to engage and excite such students in what might be argued as rather staid topics associated with, soils and rock. Student engagement is also particularly challenging as class sizes continue to grow along with the increasing demands on academics' time.

Hence, this paper proposes an approach that incorporates a variety of resources and pedagogical practices. Such an approach is not new or novel. However, never in the past has such an eclectic range of resources and the associated technology been readily available for incorporation into existing geo-engineering curricula. Hence, this paper presents a multi-faceted approach to geo-engineering education which incorporates the use of demonstration aids, e-learning, video footage and documentaries, and treatment of classic geo-engineering failures. Such an approach has been shown to enhance student engagement, improve learning outcomes and increase the students' desire to undertake careers, further study and research in geo-engineering. In addition, the paper is intended to be a resource for geo-engineering educators. Treatment begins with demonstration models.

2 DEMONSTRATION MODELS

Physical models have been used to demonstrate various phenomena in geo-engineering for decades and, in the context of undergraduate geotechnical engineering education, have been shown to assist greatly with the understanding of fundamental principles (Burland, 1987; Steenfelt, 2000). In fact, several researchers have proposed various physical demonstration models in relation to geotechnical engineering and extolled their virtues (e.g. Poulos, 1994; Andrei & Manea, 2000; Bucher, 2000; Kodikara, 2000; Wesley, 2000; Atkinson, 2007; Jaksa, 2008).

The author has found three models in particular to engage students and increase their learning. These include the *liquefaction sand column*, the *vacuum-sealed coffee brick*, and the *consolidation model*. These are described briefly in the following subsections. More detailed treatment of the models, their specifications and their demonstration is given by Jaksa (2008).

2.1 *Liquefaction Sand Column*

Lambe & Whitman (1969) introduced a conceptual model of a column of saturated sand to demonstrate the influence of pore water, excess pore water pressure and liquefaction. This concept, when in the form of a physical model, is a particularly useful teaching aid to facilitate a deeper understanding of pore water pressure, effective stress, the influence of flow direction on these, soil heave and liquefaction. Such a physical model, known as the *liquefaction sand column*, was developed at the University of Adelaide some time ago by the author's predecessors, as a laboratory-based apparatus. Recently, as shown in Figure 1, the author has adapted the liquefaction sand column to make it portable, by incorporating a small electric pump and a self-contained water supply. In this way, the apparatus can be readily used as a demonstration aid in lectures. Student feedback has shown that it greatly enhances the understanding of the concepts mentioned above. Furthermore, it generates a great deal of engagement, both with the student body, as well as the general public and potential students, when it is used as a demonstration tool at expos and the like.

Figure 1. University of Adelaide liquefaction sand column.

Briefly, the author's presentation begins by demonstrating quicksand by establishing an upward water flow in the sand column. The students are then asked whether humans sink or float in quicksand. A brief video clip is shown from a Tarzan movie (*Tarzan and the Amazons*) where Tarzan leads two villains into a 'natural quicksand' pit, whereby they are subsequently consumed by the quicksand and they sink to the murky depths. A model human is then shown – another villain, this time from the 1960s marionette sci-fi series, the *Thunderbirds* (Wikipedia 2008m). It is explained that the model (Fig. 1) is a faithful reproduction of an actual human being, in that its specific gravity is close to unity. The students are again asked to decide whether the model will sink or float in the quicksand. The model is then lowered into the 'boiling' mix and, lo-and-behold, he floats! The students are solicited to provide reasons for why he floats.

A downward flow of water is then established, followed by the creation of a v-notch, using a spatula; a stable slope results. The valve permitting the vertical downward flow is closed, thereby creating a no-flow situation. The v-notch slope then collapses a little to a shallower slope angle. The valve which allows water to flow vertically upwards is then opened, immediately upon which the v-notch slope totally collapses. The students are then asked to explain this. The relationships between vertical flow, effective stress, soil strength and slope stability are then readily established.

Finally, liquefaction as a result of an earthquake is demonstrated. The water level in the sand column is lowered to just below the sand surface, thereby simulating the condition that occurred in Niigata prior to the 1964 earthquake (see §5.5 below). A heavy brass model of a multi-storey building is then placed on the sand surface. The building settles a reasonable amount when founded on the loose, saturated sand. A gentle tap on the side of the sand column causes the soil to liquefy and the building to collapse, similar to the buildings in Niigata (Fig. 2). The students are then asked to explain this.

A Mythbusters episode (Mythbusters, 2004) also deals with a full-size quicksand experiment.

Figure 2. Liquefaction foundation failure due to 1964 Niigata earthquake. (Source: Penzien, 1964)

2.2 *Vacuum-sealed Coffee Brick*

The author has found, as have others (e.g. Atkinson 2007), that a readily available and extremely useful physical example of the concept of effective stress is a vacuum-sealed brick of ground coffee – a typical example of which is shown on the right in Figure 3.

Figure 3. Typical bricks of ground coffee.

At the beginning of the author's lecture on effective stress, two bricks of vacuum-sealed ground coffee are handed around the lecture theatre. It is pointed out that one has been punctured beforehand, thus compromising the vacuum seal, while the other has not been tampered with. The punctured brick is relatively soft and the coffee grains can be easily moved around inside the packet, as shown on the left in Figure 3. In contrast, the other intact vacuum-sealed brick is very hard and almost impossible to distort or indent with a finger. The author asks the class to feel both bricks, postulate, in their own minds, the reason for the difference between them, and then pass them on to the next student. Whilst the students are doing this, the lecture on effective stress proceeds.

At the end of the lecture the author asks whether anyone can suggest the reason for the difference between the two bricks. The answer, of course, is that the vacuum seal has increased the inter-granular stress, i.e. the effective stress, and, hence, the friction between the coffee grains, and therefore the strength of the particulate mass. In this example, the pore fluid is air rather than water, and the pore air pressure is negative, due to the vacuum. The effective stress is therefore greater due to the negative pore pressure.

A similar example to the vacuum-sealed coffee brick is that mentioned by Poulos (1994). It consists of a rubber glove filled with dry sand. When air is removed from the glove, by means of a vacuum, it increases in strength and is able to grasp a hammer.

A further example of the increase in strength of a particulate mass is that of a *vacuum mattress*. Such mattresses are used by emergency rescue personnel as a stretcher over short distances and to immobilise patients, especially in cases of vertebra, pelvis or limb trauma. As shown in Figure 5, the mattress is a sealed polymer bag (larger than an adult human body) that encloses small polystyrene balls, with a valve, straps and handles (Wikipedia, 2008n). In its inoperable state, when the mattress valve is open and exposed to atmospheric pressure, the balls are relatively free to move and the mattress can be moulded beneath and around the patient. Air is then withdrawn from the mattress through the valve by means of a hand-operated pump and the valve is closed. The suction causes the balls to press together and the mattress becomes hard and rigid.

Figure 4. Vacuum mattress with hand pump.
(Source: Wikipedia, 2008n)

2.3 *Consolidation Model*

Finally, a model that very effectively demonstrates the process of consolidation, as well as effective stress, is that shown in Figure 5, as suggested by Terzaghi. When converted to a physical model and used in lectures, students are readily able to understand the consolidation process, excess pore water pressure and consolidation settlement. Limitations of space do not permit a more detailed description of this model. Jaksa (2008), however, provides treatment of the model's specifications and the demonstration itself. Several text books (e.g. Lambe & Whitman, 1969; Holtz & Kovacs, 1981) also discuss this model in conceptual terms.

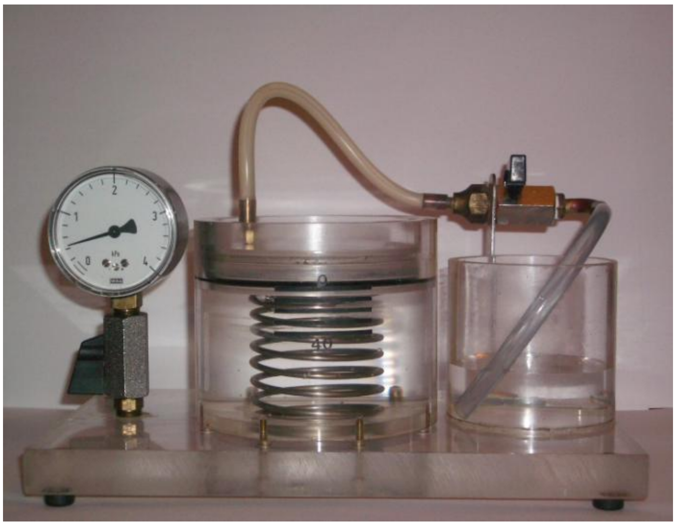

Figure 5. Consolidation model.

3 E-LEARNING

A valuable additional resource to facilitate effective and efficient student learning and further engage students is the use of e-learning, such as computer aided learning (CAL) and web-based learning (WBL) (O'Neil & Perez, 2006). Jaksa et al. (2000) presented a detailed overview of CAL and WBL resources available in geo-engineering at the time, as well as the benefits and limitations of CAL. In relation to geotechnical engineering, most notable of these is the *GeotechniCAL* suite of programs (Davison, 1996), *CATIGE* (Jaksa et al. 1996), *CIVCAL* (CIVCAL, 2000), Delft Resources (Verruijt, 2008) and *Excavate* (Yuen et al., 2005). In addition, several geo-engineering software companies provide student versions of their programs at no cost (e.g. Geo-slope Int., 2008; SoilVision Systems, 2008; Centre for Geotechnical Research, 2008). The author uses various CAL modules in lectures as a demonstration aid to reinforce key concepts and makes the various programs available for the students to use as part of their private study.

In general, significant amounts of time and funding are required to develop CAL resources. Operating systems and programming languages are frequently updated and, as a consequence, the CAL resources require regular maintenance, which is often not a trivial task.

4 DOCUMENTARIES

Particularly with the advent of pay-television (cable) services, the production of engineering-related documentaries has increased greatly over the last 5-10 years. These programs are regularly scheduled on many of the cable channels, most notably the Discovery and the National Geographic Channels and, to a lesser extent the History Channel, and they make for fascinating viewing. Table 1 lists examples of such series and episodes which are particularly relevant to geo-engineering. In most cases, the references provide a complete list of episodes which cover the broader civil and other engineering-related topics. Whilst Table 1 lists the episodes which are more related to geo-engineering themes, many of the episodes, related more to general civil and structural engineering, also include some aspect related to geo-engineering, as one might expect.

More recently, with the advent of writable digital video discs (DVDs) and computer-based movie editing software, it is relatively straightforward for the geo-engineering educator to record such documentaries and edit them to provide relevant and engaging video footage to enhance lectures and facilitate greater student engagement.

Table 1. List of geo-engineering-related documentaries.

Series (references) and Episodes
Building Big (Building Big, 2000): Dams; Tunnels
Building the Biggest[D] (Discovery Channel, 2008b): Diamond Hunters; Underground Singapore
Decoding Disaster: Mudslides
Disasters of the Century[H] (Partners in Motion 2004): Black Week (Senghenydd mine collapse); Communities Under Siege (1958 Springhill Mining disaster); In an Instant (Vajont Dam failure); Living on the Edge (Frank Slide, Hillcrest Mine disaster); When the Earth Moves (1923 Great Kantō earthquake, 1972 Managua, Nicaragua earthquake)
Extreme Engineering[D] (Discovery Channel, 2008a): Boston's Big Dig; Building Hong Kong's Airport; Malaysia Smart Tunnel; Subways in America; Three Gorges – The Biggest Dam in the World; Transatlantic Tunnel; Tunneling Under the Alps; Widening the Panama Canal
Frontlines of Construction[NG] (DigiGuide, 2008): Blasting; Danger; Defying Gravity; Disaster; Dubai's Palm Island; Hammer This!; Mega Machines; Oasis; Offshore; Risk Top Ten
Frontiers of Construction: A Giant Out of Water (Chek Lap Kok Airport); The Big Dig; Dubai – City of Dreams; The Eurotunnel; Heavy Traffic; The Oresund Link
Kings of Construction[D]: Hallandsas Tunnel; Hoover Dam Bridge; South Ferry Subway Terminal
Man Made Marvels[D] (Discovery Channel, 2008c): Taiwan's Hsuehshan Tunnel
Mega Builders[D] (Barna-Alper, 2008): Madrid's Big Dig; Moving Mountains; Palm Islands; Quake Proofing an Icon; Saving New Orleans
Megastructures[NG] (Wikipedia, 2008f): Boston's Big Dig; Channel Tunnel; Deep Sea Drillers; Diamond Diggers; Garbage Mountain; Hoover Dam; Itaipu Dam; Kansai Airport; Megabridges – China; Megabridges – Denmark to Sweden; Megabridges – Greece Rion-Antirion Bridge; Rock Breakers of Iceland; Millau Bridge; North Sea Wall; Panama Canal Unlocked; Petronas Towers; Port of Rotterdam; Ultimate Oil Rigs; World Island Wonder
Modern Marvels[H] (Wikipedia, 2008g): Aswan Dam; China's Great Dam; The Chunnel; Dams; Diamond Mines; Engineering Disasters (1-21); Gold Mines; Grand Coulee Dam; Panama Canal; Quarries; Suez Canal; Tunnels; World's Biggest Machines
Seconds From Disaster [NG] (National Geographic, 2008): Flood at Stava Dam; Killer Quake (Kobe Earthquake); Mount St. Helens Eruption
Seismic Seconds[NG] (Wikipedia, 2008j): The Eruption of Mount Saint Helens; Sarno Slides; Teziutlan Slides
Various: Legacy: St. Francis Dam Disaster with Frank Rock; Catastrophe: San Francisco Earthquake[D]; China's Mega Dam – The Three Gorges Dam[D]; Extreme Earth - Saving Our Crumbling Coastlines[D]; Landslides – Gravity Kills; Tunnels - Digging in[D]; When Nature Strikes Back – Landslides[D]; Ultimate Earthquake Disaster[NG]; Wild Weather – Landslides

D: Discovery Channel; H: History Channel; NG: National Geographic Channel.

5 GEO-ENGINEERING CASE STUDIES AND FAILURES

It is well-appreciated that the examination of case studies, and particular those associated with failures is central to rigorous engineering design (see Petroski, 1985, 1994, 2006; Levy & Salvadori, 1992). The author has found that student engagement is greatly enhanced by integrating relevant treatment of geo-engineering failures into the curriculum. An essential aspect of sound engineering practice, and therefore education, is ensuring that lessons are learnt from the mistakes of the past. Morley (1996) attests that analyses of failures can teach lessons that are often missing in success stories. The following sub-sections provide brief treatment of some of the more notable geo-engineering failures which highlight important lessons for the profession and, hence, the student. References are given to important publications associated with each failure, as well as links to websites which provide useful information, photographs, illustrations and video footage, where available. Wikipedia provides an excellent resource for many of the failures described below.

5.1 *Leaning Tower of Pisa*

Without doubt, the most significant icon of geotechnical engineering is the Leaning Tower of Pisa. Students and the public alike instantly relate to and engage with the history and drama of the tower. Papers which detail the geotechnical engineering aspects of the tower include Terzaghi (1934), Terracina (1962), Mitchell et al. (1977), Leonards (1979), Levy & Salvadori (1992), Burland & Potts (1994), Morley (1996), Rampello & Callisto (1998). Recent successful stabilization works to the tower have showcased the value and effectiveness of geo-engineering. Details of these stabilization works are given by Burland et al. (1999) and Burland (2001).

5.2 *Dam Failures*

Several significant and tragic dam failures highlight a number of important issues useful for the education of future geo-engineers. Wikipedia (2008d) provides a list of the major dam failures. Ones which are particularly engaging, and with important geo-engineering lessons, include the following:

- *Vajont (also Vaiont) Dam failure, 1963*: Strictly a landslide and not a dam failure, as the dam remains in place today impounding debris rather than water, the dam is located in a very steep valley in the Italian Alps, 160 km north of Venice. The dam was designed to produce hydroelectric power for the region and construction was completed in 1960. At the time, it was the thinnest concrete arch dam in the world and stands 265 m high. After a week of heavy rainfall, a massive, 1.5 km long, landslide on the banks of the Vajont reservoir, 270 million m^3 in volume, displaced the entire reservoir, 700 m in depth, in 15-30 seconds, causing a tidal wave to overtop the dam by 100 m and crash down into the narrow gorge below. The consequent air pressure wave and flooding of several villages downstream resulted in the loss of 2,043 lives, making the Vajont disaster the worst dam failure in history. The tragedy highlights the lack of attention given to engineering geology. Details of the failure are given by Kiersch (1964), Skempton (1966), Broili (1967), Chowdhury (1978), Hendron & Patton (1985), Voight & Faust (1992), Wearne (1999), Glastonbury & Douglas (2000), Petley (2001) and Losso (2005).
- *Malpasset Dam failure, 1959:* The Malpasset was a double-curved concrete arch dam on the Reyran River in southern France and was constructed to provide water and irrigation for the region. The entire wall collapsed on December 2, 1959, with the resulting flood killing 421 people and causing $US68 million in damage. Like the Vajont Dam, the Malpasset failure highlights the importance of engineering geology. Further information regarding the Malpasset dam failure is given by Bellier (1967), Habib (1987), Londe (1987), Serafim (1987), Levy & Salvadori (1992) and Wikipedia (2008e).
- *Teton Dam failure, 1976:* The Teton was an earth-fill dam constructed in early 1970s for the supply of irrigation water, flood protection and power generation. The reservoir began filling on October 3, 1975 and the dam failed on June 5, 1976 (Fig. 6). Despite evacuating townships downstream, 11 people died, more than 2,000 were injured and 25,000 were left homeless. The total cost associated with the failure is estimated to be $US2 billion. At the time of failure, the reservoir was almost full and contained 310 million m^3 of water. After the breach the main part of the reservoir emptied in about 5 hours. The failure highlights the importance of understanding the mechanism of piping, although consensus has yet be established in relation to the cause of the failure. Details of the failure are given by Seed & Duncan (1987), Sherard (1987), Stene (1996), Sylvester (2008).

Figure 6. Teton dam failure. (Source: Mrs. E. Olson [Sylvester, 2008])

- *Stava Dam failure, 1985:* The Stava Dam (also Val di Stava Dam) was actually two dams, one located above the other, that were used to impound tailings from a fluorite mine above the village of Stava in northern Italy. On July 19, 1985 the dams failed resulting in 268 lives lost, the destruction of 62 buildings and 8 bridges and $US200 million in damage. It was one of the worst industrial disasters in the world. The upper dam failed first, leading to the collapse of the lower dam. The collapse released approx. 200,000 m^3 of debris which flowed into the Rio di Stava valley at speeds of 90 km/h. The failure highlights the importance of maintenance and appropriate design factors of safety. Details of the failure are given by Chandler & Tosatti (1995), Berti et al. (1997), Blight & Fourie (2003), Stava 1985 Foundation (2008), Tailings.info (2008) and Wikipedia (2008o).
- *St. Francis Dam failure, 1928:* The St. Francis Dam was a concrete gravity-arch dam, constructed between 1924 and 1926 to create a reservoir for the Los Angeles Aqueduct. The dam was located 64 km northwest of Los Angeles, California. Three minutes before midnight on March 12, 1928, the dam collapsed, and the resulting flood killed more than 600 people. The St. Francis Dam failure is the worst American civil engineering disaster of the 20th century and is the second-greatest loss of life in California's history, after the 1906 San Francisco Earthquake and fire. Further information is available by Wikipedia (2008k).
- *South Fork Dam failure, 1889:* The South Fork Dam was constructed to provide water for the section of the Pennsylvania Canal between Johnstown and Pittsburgh and was completed in 1852. Almost immediately after that the canal system became obsolete. In subsequent years minimal maintenance was performed on the dam, even though a minor failure occurred in 1862 when the reservoir was half full. On May 31, 1889, a large storm led to the collapse of the neglected dam and the consequent downstream flood resulted in the loss of 2,209 lives. The failure highlights the importance of appropriate spillway design and maintenance. Details of the failure are given by Connelly & Jenks (1889), Levy & Salvadori (1992), Johnstown Flood Museum (2008), Rogers (2008) and Wikipedia (2008b).

5.3 *Landslides and Sinkholes*

Wikipedia (2008c) and Broms & Wong (1991) contain lists of the more significant landslides. The following have been found by the author to be particularly relevant to student engagement and geo-engineering education.

- *Aberfan, 1966:* At 9:15 am on 21 October 1966, a landslide involving a coal tip slag heap occurred in Aberfan in South Wales involving 100,000 m^3 of colliery waste (Fig. 7). Downslope and in the direct path of the debris landslide was a junior school and, of the 144 people killed, 116 were children, most between the ages of 7 and 10 (Johnes & McLean, 2006). The Report of the Inquiry (Davies, 1967) held after the disaster attributed blame solely to the National Coal Board. The Report stated:

  "*the Aberfan Disaster is a terrifying tale of bungling ineptitude by many men charged with tasks for which they were totally unfitted, of failure to heed clear warnings, and of total lack of direction from above.*"… "*Not villains but decent men, led astray by foolishness or by ignorance or by both in combination, are responsible for what happened at Aberfan.*"

  Further information is available from Davies (1967), Bishop et al. (1969), Johnes & McLean (2006), George & Matsell (undated). Blight and Fourie (2003, 2005) provide lists of notable mine waste failures.

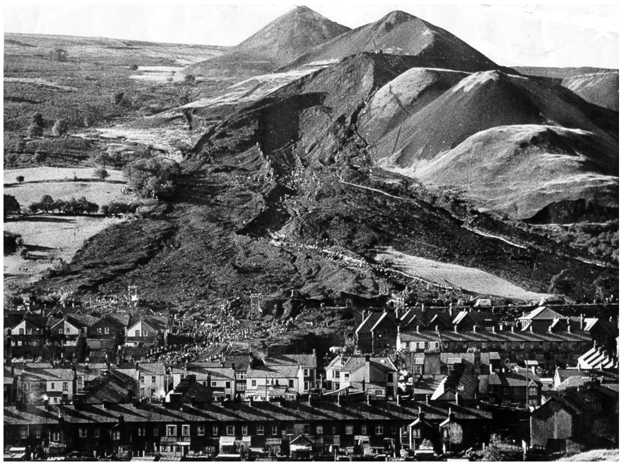

Figure 7. Aberfan landslide (Source: Johnes & McLean, 2006).

- *Saint-Jean-Vianney, 1971:* Saint-Jean-Vianney was a village in the Saguenay-Lac-Saint-Jean region of Quebec, which was partly destroyed by a quick clay landslide on May 4, 1971 (Fig. 8). At the time of the landslide the village's population was around 1,300. Following unusually heavy rains in April of 1971, the Leda clay sub-soil became saturated as a result of restricted drainage. The Leda clay underlies extensive areas of the Ottawa-Gatineau region of Canada and is composed of clay- and silt-sized particles that were finely ground by glaciers and washed into the Champlain Sea (Natural Resources Canada, 2008). As the particles settled through the saline water, they were attracted to one another and formed loose clods that fell to the seafloor. The resulting sediment has a loose but relatively strong soil structure. Inflow of fresh water results in leaching of the salts which significantly reduces the particle bonds and hence soil strength. The combination of fresh water inflow and a triggering mechanism (e.g. river erosion, increases in pore water pressure – especially during periods of high rainfall or rapid snowmelt – earthquakes, and human activities such as excavation and construction [Natural Resources Canada, 2008]) has resulted in over 250 catastrophic landslides in the Quebec region of Canada, and as detailed below in Norway (see Rissa landslide, below) and Sweden (Rankka et al. 2004). The most disastrous Leda clay landslide in eastern Canada occurred in 1908 at Notre-Dame-de-la-Salette, Quebec, with the loss of 33 lives (Natural Resources Canada, 2008).

In the few weeks leading up to the Saint-Jean-Vianney landslide, cracks were reported in some of the village's streets and driveways, with some house foundations having settled approximately 150-200 mm. At 10:45 p.m. on the evening of May 4, the earth suddenly dropped approximately 30 m, forming a large canyon through which a river of liquefied clay flowed toward the Rivière du Petit-Bras below, engulfing several houses in its path. Just before midnight, the clay finally stopped flowing and began to resolidify. The landslide consumed 41 houses and 31 people were killed (Wikipedia (2008i). Further details are given by Tavenas et al. (1971), Eden et al. (1971), Smalley et al. (1975), Looker (2000), Rankka et al. (2004), Lamontagne et al. (2007), Natural Resources Canada (2008) and Wikipedia (2008h, i).

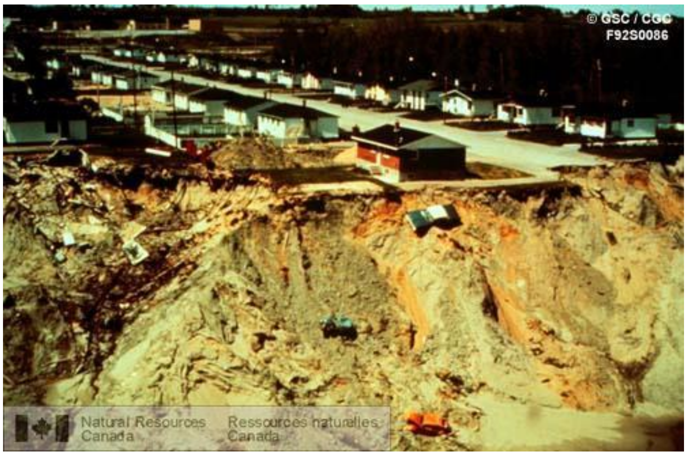

Figure 8. Saint-Jean-Vianney landslide (Source: Natural Resources Canada).

- *Rissa, 1978:* An excavation associated with the construction of an addition to a barn in Rissa, Norway, led to a retrogressive quick clay landslide in April, 1978, which claimed several properties and structures and fortunately without loss of life (Fig. 9). The quick clay soil is similar in nature to the Leda clay described above. The landslide was filmed by two amateur photographers and a 30 minute documentary including this footage has been produced by the Norwegian Geotechnical Institute and a video and DVD are available for purchase from them. The documentary makes for fascinating viewing. Edited highlights of the documentary are available for download from Norwegian Geotechnical Institute (2008). Further details are given by Bjerrum (1955), Norwegian Geotechnical Institute (2008) and Wikipedia (2008h).

Figure 9. Rissa landslide (Source: Norwegian Geotechnical Institute, 2008).

- *Frank Slide, 1903:* Another significant Canadian landslide occurred in the coal mining town of Frank, Alberta, with a population of 600 people. At 4 am on April 29, 1903, approximately 70-90 million tonnes of limestone slid from the summit of Turtle Mountain and covered approximately three square kilometres of the valley floor (Looker, 2000). About 70 individuals were killed and numerous buildings were demolished. Further details are given by Anderson (1968), Cruden & Krahn (1978), Benko & Stead (1998), Glastonbury & Douglas (2000), Looker (2000) and Wikipedia (2008a).
- *Thredbo, 1997:* At approximately 11:30 pm on July 30, 1997, a landslide occurred at the Thredbo Ski Village in Kosciusko National Park, New South Wales, Australia (Fig. 10). According to the Coroner (Hand [2000]), the landslide was initiated in the fill embankment of the roadway (Alpine Way) above the Carinya Lodge. Carinya was a ski club lodge occupied, at the time, by one person. In a matter of seconds the first movement of the landslide impacted on the east wing of Carinya, tearing the lodge in two and projecting the east wing to the north-east. A second movement of the landslide then occurred which sheared the Carinya Lodge from its foundations and projecting it into Bimbadeen Lodge causing it to collapse. Eighteen people were in that lodge at the time. Of the 19 people in the two lodges 18 died as a result of the landslide. It was the worst natural disaster in Australian history. A rescue

operation was immediately mounted, where one fortunate survivor was located on 2 August, 1997. Hand (2000) concluded that the landslide was caused by a leaking fire main constructed some 13 years earlier along the Alpine Way and which had fractured some time prior to the tragedy as result of soil creep in the slide zone. However, an important lesson was that crucial site information had been 'forgotten' in the passage of time. The Alpine Way had been built as a construction road by the Snowy Mountains Hydro-Electric Authority in about 1955 for light traffic and with a design life of 20 years. The Alpine Way was constructed by side-casting down-slope loose fill comprising topsoil, colluvium, boulders, tree stumps, logs and vegetation. The down-slope fill was not compacted and, as a result, the slope was only marginally stable. Numerous landslips had occurred along the length of the Alpine Way over the years and the site where the Carinya and Bimbadeen Lodges were built was considered too unstable to permit the construction of buildings. The history of the region was well known, although not documented in any systematic fashion. Information regarding the construction of the Alpine Way was not passed on. In addition, the large number of landslides in the region, prior to Thredbo, were not acted upon. Further details of the landslide are given by Hand (2000), Mostyn & Sullivan (2002) and Wikipedia (2008l).

- *Waihi Sinkhole, 2001:* At 12:15 am on 13 December 2001, a 40 to 50 m diameter, 10 m deep crater formed suddenly in the gold mining town of Waihi, New Zealand, leaving one house demolished on the floor of the crater and two others perched on the edge (Fig. 11). The 5 occupants of the wrecked house were unharmed. This event follows similar ones in 1961 and 1999. Waihi is home to the Martha gold-silver mine that operated between 1882 until 1952, with shafts and workings reaching a total depth of approximately 600 m on 16 levels to mine the steeply dipping ore bodies. The gold-silver bearing reefs extended laterally for up to 1.6 kms. The Martha underground mine became established as one of the great mines of the world. In the early years of mining, the stopes were backfilled with waste rock, but after 1914 this practice was generally abandoned and the stopes were commonly left empty. The sinkholes are the result of chimneys which form due to stope roof collapse which progresses to the ground surface. Further information is given by Jennings et al. (2000) and Dennison (2002).

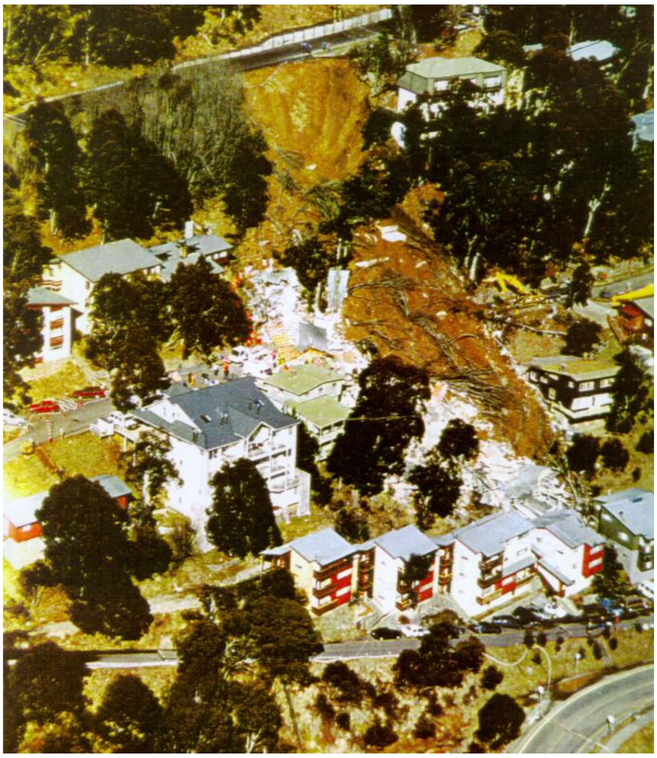

Figure 10. Thredbo landslide (Source: Hand, 2000).

Figure 11. Waihi sinkhole (Source: Dennison, 2002).

5.4 *Bearing Capacity Failures*

Two notable bearing capacity failures are the Transcona and the Fargo Grain Elevators. The Transcona grain elevator (silo) was built in 1911 in Winnipeg, Canada. It consisted primarily of 65 reinforced-concrete cylindrical bins arranged in 5 rows, with 13 bins in each row. The grain elevator was approx. 60 × 25 m in plan × 30 m high. The 65 bins were founded on a raft footing, about 0.6 m thick. On October 18, 1913, the bin house began to move slightly. A vertical settlement of 300 mm occurred within one hour. The following day, it came to rest, leaning at a vertical angle of 27° (Fig. 12). The eastern side of the structure had risen 1.5 m above the ground level and the western side had settled by almost 9 m. Although it is a very large and heavy structure, it remained undamaged with only very minor cracking. As a result, it was decided to repair the structure. In late 1913, work began to right the elevator and by October 1914, the structure was again made vertical.

It was, however, 4.27 m below ground level. Further information is available from Peck & Bryant (1953) and Scott White (1953).

Early on the morning of June 12, 1955, the grain elevator built near Fargo, North Dakota collapsed as it was being filled and was completely destroyed (Fig. 13). Nordlund & Deere (1970) concluded that the collapse was a classic example of a full-scale bearing capacity failure, which could have been avoided had rudimentary soil testing and bearing capacity analyses been carried out.

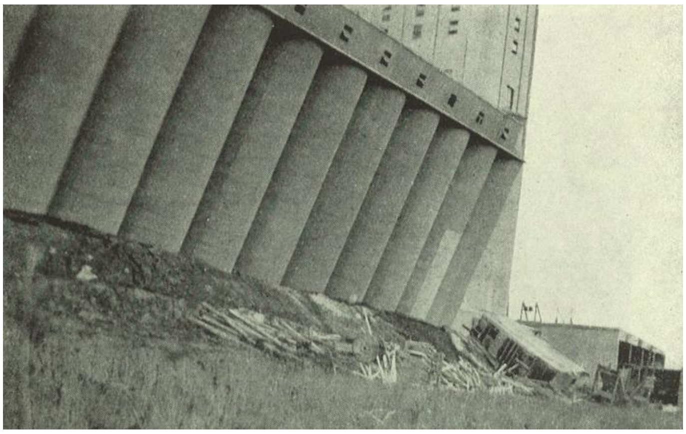

Figure 12. Transcona grain elevator failure. (Scott White, 1953)

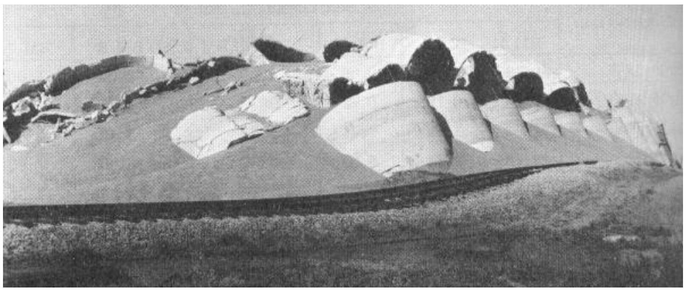

Figure 13. Fargo grain elevator failure. (Nordlund & Deere, 1970)

5.5 *Other Geo-engineering Failures*

Other notable geotechnical failures include the:

- *Niigata earthquake, 1964,* with its unique apartment building foundation failures as a result of liquefaction (Fig. 2). Refer to Seed & Idriss (1967), Levy & Salvadori (1992) for additional information.
- *Schoharie Creek, 1987,* involves the scouring failure of a bridge abutment during high river flows. On the morning of April 5, 1987, two spans of the 30 year old New York State Thruway bridge over the Schoharie Creek collapsed. Five vehicles fell into the swollen river, killing 10 of the occupants. Further information is given by Wiss et al. (1987), Thornton et al. (1988), Levy & Salvadori (1992) and Wearne (1999).
- *Bulbul Drive landfill failure, 1997:* The Bulbul Drive landfill, in the outskirts of Durban, South Africa, is situated at the head of a valley with a base slope of 7° and side slopes of up to 19° (Blight, 2004). The landfill, which co-disposes municipal and industrial waste, failed suddenly on the evening of 8 September 1997, after a period of two days of light rain. Approximately 160,000 m^3 of waste slid down the valley (Fig. 14). As the failure occurred at night, no one was injured as a consequence of the failure (Blight, 2004). Further information is given by Brink et al. (1999), Blight (2004) and Dixon & Jones (2005). Blight & Fourie (2003, 2005) and Dixon & Jones (2005) also provide lists of notable landfill failures.

Figure 14. Bulbul Drive landfill failure. (Source: P.W. Day)

- *Loscoe landfill gas explosion, 1986:* In March 1986 a house in Loscoe, Derbyshire, was destroyed by a methane gas explosion, badly injuring its three occupants. The source of the methane was later found to be a nearby unlined landfill. Further details of the explosion are given by Derbyshire County Council (1988), Williams & Aitkenhead (1991) and Enviros Consulting (undated).
- *Port Broughton, 2000:* The author was personally involved in a forensic geo-engineering investigation of a failure which involved the deaths of two persons in Port Broughton, South Australia. The accident occurred on May 28, 2000, when a transportable house, which was being relocated from another South Australian country town, fell suddenly killing two of the 6 people beneath or adjacent to the house at the time. The house had stood elevated on 6 mechanically-operated jacks for a period of ¾ hour before it collapsed. The cause was attributed to differential settlement of the jacks due to the combination of collapsing soil, load, and rain which had fallen for the two days immediately prior to the collapse. Jaksa (2007) provides further detail.

6 CONCLUSIONS

This paper has focussed on enhancing student learning by means of increasing engagement. It is suggested that a multi-faceted approach to geo-engineering education, that is one which incorporates a variety of teaching aids, enhances student engagement and achieves improved learning outcomes. Student surveys carried out by the author over several years demonstrate the value of such an approach. The paper advocates the use of traditional forms of instruction, such as lectures and tutorials, which are made richer by the use of demonstration aids, e-learning, video footage and the treatment of classic geo-engineering failures.

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