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Sport and Soil Mechanics – analogies to aid student learning

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ABSTRACT: It is well recognised that students' understanding of complex ideas can be aided by analogies with separate topics, preferably in an unrelated subject area (in this case, outside of engineering). Additional benefits may be gained by having a suite of such linkages between the subject area being taught (e.g. soil mechanics) and one common analogy area (e.g. sport), as a means of consolidating several new concepts. Sport tends to have a broad appeal among engineering students and the authors have found that sporting analogies have proven effective in teaching certain soil mechanics concepts. The purpose of this paper is to bring a few of these analogies together into a single engaging and fun document to be made available to students taking introductory soil mechanics courses.

1 INTRODUCTION

Many engineering subject areas taught at university are founded on a few core concepts and principles which are often elusive to students, and soil mechanics is no exception. For example, the challenge of teaching a fundamental soil mechanics concept, *effective stress*, has been illustrated by the results of a survey of Irish geo-engineering practitioners reported by McCabe and Phillips (2008). From a list of six topics including effective stress, basic parameters (such as water content, Atterberg limits, density, void ratio etc.), shear strength, compressibility, permeability/groundwater flow and stress beneath loaded areas, respondents surprisingly ranked effective stress as the least relevant of these to their work even though it underpins most of them. Atkinson (2008) lists an over-emphasis on standards and codes ahead of basic principles and a stagnant "*teach what I was taught*" approach in university education among several reasons why some geotechnical engineers may be lacking in competence.

On a positive note, several authors have shared the instruction strategies that they use to promote effective student learning in soil mechanics and geotechnical engineering modules. Airey (2008) discusses the merits of learning through laboratory and analytical/numerical projects. Geotechnical case histories can serve as a powerful tool for teaching (e.g. Phillips 2008) and Orr and Pantazidou (2012) consider the relationship between specific learning outcomes and the corresponding suitable types of case studies and case data. Jaksa (2008) advocates the use of a multi-faceted approach to soil mechanics instruction, and provides a comprehensive list of resources (including physical demonstration models, videos and case history/failure references) which have been used with success.

In the context of engineering education, Felder and Silverman (1988) state that "*students learn in many ways — by seeing and hearing, reflecting and acting, reasoning logically and intuitively, memorizing and visualizing and drawing analogies and building mathematical models; steadily and in fits and starts*." An analogy is a teaching strategy which uses a concrete reference to develop a comprehension of something more abstract. When used carefully, Dagher (1995) has shown that analogies can be an effective means of communicating scientific concepts. Donnelly and McDaniel (1993) used multiple-choice testing to compare learning of scientific concepts expressed in either traditional literal form or through an analogy. While basic-level questions were answered most accurately when concepts were expressed literally, more difficult questions were answered most accurately when concepts were expressed analogically. However, more effective cognitive transfer is not the only benefit of using appropriate analogies in teaching; Heywood and Parker (2010) and others have recognised their effectiveness in engaging students in the learning process. The authors of this paper also propose that additional benefits may be gained by having a suite of linkages between the parent subject area being taught and one common analogy area.

Sport tends to enjoy a broad appeal among students of civil and environmental engineering and construction-related programnmes, and in this paper, the authors show how four important areas of soil mechanics can be explained with simple analogies to various sports or sports-related activities. The paper is intended to serve as a self-contained, engaging and fun document for use in parallel with introductory soil mechanics modules, and it is hoped that the cumulative effect of grouping a few sporting analogies together here might be greater than if they were considered individually.

2 WEIGHTLIFTING AND STRESS HISTORY

The idea that the stress to which ground was subjected in the past (possibly thousands of years ago) can have a major bearing on its strength and stiffness today can be an alien concept to engineering students as it is not a feature of the other materials, such as concrete or steel, with which they are familiar. Weightlifting (or muscle building in general) can be used to help to explain the significance of stress history in soil mechanics and to define the overconsolidation ratio (OCR); the ratio of the maximum previous vertical effective stress (known as the preconsolidation or yield pressure) σ'_{vy} to the current vertical effective stress σ'_{v0}. A cartoon such as that shown in Figure 1 is an excellent way to capture students' attention in the classroom before an explanation of the analogy unfolds, as follows:

(i) Lifting weights of a sufficiently high intensity causes muscle fibres to tear but they repair themselves within a couple of days and become stronger than they were originally. Improvements to strength will accrue over time if weightlifters continue to push their boundaries. The stronger the arm muscles (for example) are, the less the effort associated with everyday lifting (such as several bags of shopping).

(ii) Soil that is strong and stiff today has previously been subjected to much higher stresses than it is currently experiencing, or alternatively phrased, the current stress in the soil falls below its preconsolidation or yield pressure. By way of analogy, someone who has previously loaded muscles to high stresses (the highest being the muscle's yield stress) will be strong and therefore should find the muscle stress imposed by the bags of shopping to be relatively comfortable.

(iii) The analogy can be extended further by considering the ratio of the maximum weights lifted by the weightlifter in the gym to the weight of the shopping bags. The higher this ratio, the easier the act of carrying the shopping will be. In soil mechanics terms, a similar ratio applies (OCR$\geq$1) as defined above. A weaker person will find the same bags more difficult to carry, as the muscle stress involved will be closer to their muscles' yield point (i.e. lightly overconsolidated, low OCR value) or may even surpass the previous yield point to create a new one (normally consolidated, OCR=1). A stronger person can lift shopping bags with ease, as the stress on the muscles is well below yield and the muscle can be thought of as heavily overconsolidated (i.e. it has a high OCR value, OCR>>1).

(iv) This is a good stage to explain why specific soil types have different OCR values; for example a strong and stiff high OCR glacial till may once have been subjected to the weight of up to 1km of glacial ice, whereas a soft and compressible estuarine deposit will have a low OCR as it will be at or close to its highest ever stress level. This serves as a convenient lead-in to a more thorough explanation of the process using e-log σ'_v curves (e = void ratio).

The analogy has been found to be effective in indicating that stiffness and strength of soil are dependent on previous stress levels in the same way as that the strength of a weightlifter is dependent on the degree to which he/she has extended his/her muscles in the past. It is pointed out to the students that we normally talk about muscle strength and not stiffness, so strength and stiffness are used somewhat interchangeably here with the purposes of explaining the concept (which of course is not generally appropriate in engineering).

Figure 1: "POPEYE" cartoon used in lectures to introduce the muscle building and stress history analogy

3 VARIOUS SPORTS BALLS AND SPECIFIC SURFACE AREA

Atkinson (2007) indicates that coarse-grained soils (silt-sized and coarser) essentially behave like an assembly of marbles of different sizes whereas clays have two main features which distinguish them from fine-grained soils. Clay grains can change in volume significantly as the loading and water content changes. Also, the effect of a small electrical charge carried by clay grains becomes significant. As particle sizes decrease, the surface forces diminish with the square of the effective diameter, whereas the self-weight forces diminish with the cube; consequently the effects of surface forces are relatively more important in fine-grained than coarse-grained soils. This phenomenon is captured by a quantity called the Specific Surface Area (SSA); defined as the surface area per unit mass. Typical ranges for three clay minerals and clean sand are shown in Table 1 (after Atkinson, 2007).

Table 1: SSA values for clay minerals and clean sand (after Atkinson 2007)

Soil grain	**SSA (m^2/Mg)**
Kaolinite	[1-2] × 10^7
Illite	[0.65-2.0] × 10^8
Montmorollinite	up to 840 × 10^8
Clean sand	200

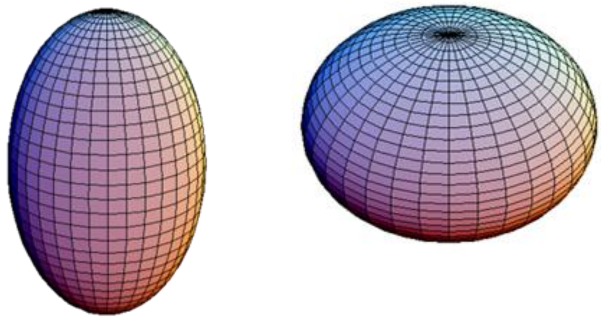
Without any prior knowledge of soil particle shapes or sizes, the default assumption that students make is that soil particles are spherical. Therefore the idea of SSA can be introduced in a fun way by asking them to rank a number of balls used in various sporting activities in order of SSA. The ranking for eight such balls is listed in Table 2; based on typical mass and diameters values derived from the internet. The students respond competitively and many succeed in placing the volleyball and the 10-pin bowling ball correctly at the ends of the spectrum, although the intermediate ones are naturally much more difficult to position correctly. They learn that it is not just diameter (and hence surface area) that governs SSA, but that density is also relevant. Students are then referred to the values in Table 1 to help them put the values for real soils in the context of those calculated for the various sports balls.

Table 2: SSA values for various sports balls

Ball	**Mass (g)**	**Diameter (mm)**	**SSA (m^2/Mg)**
Volleyball	270	210.1	513.5
Roulette ball	1	10	314.2
Basketball	600	243.5	310.5
Tennis ball	56.7	63.5	223.4
Golf ball*	45.93	42.67	124.5
Cricket ball	160	72.3	102.5
Pool ball	160	57	63.8
10-pin bowling ball	7200	218	20.7

*Dimple free golf ball assumed

Once this concept is understood, the idea of particle shape can be introduced by asking them which of a rugby ball (or any oblong ball such as an American or Australian Rules football) and soccer ball, assuming the same volume in each case, has the greater SSA. Most guess correctly based on intuition that the rugby ball has the greater surface area per unit volume. It can then be mentioned that clay particles tend not to be spherical in shape but tend to be either platy or needle-like and have even higher SSA values than spheres of the same volume. Oblate and prolate spheroids (i.e. deformed spheres, see Figure 2) can conceptually (if not strictly) be analogised with platy and needle like shapes respectively. For the more mathematically-inclined students, a comparison of the surface areas per unit volume of oblate and prolate spheroids (the latter is the rugby ball shape) with that of a sphere can be implemented in a spreadsheet. The equations for surface area (S) are given below where a and b are half the major and half the minor axis lengths of the spheroids respectively and the value of k is common to both equations. The comparison requires a condition of equal volume to be imposed, i.e. $r^3=a^3b$ (where r is the sphere radius).



$$S = 2\pi\left(a^2 + \frac{ab}{k}\sin^{-1}k\right) \qquad S = \pi\left(2a^2 + \frac{b^2}{k}\ln\left(\frac{1+k}{1-k}\right)\right)$$

$$k = \sqrt{1-\frac{a^2}{b^2}}$$

Figure 2: Prolate (left) and oblate (right) spheroids and associated equations for surface area used to help conceptualise the influence of shape on SSA.

Finally, it is highlighted to the students that in real clay soils, behaviour is likely to be influenced by a diffuse double layer and the formation of peds (stacks of individual particles), and as such, the surface area available for physic-chemical reactions is reduced.

4 POOL BALLS AND VOLUME CHANGES IN SANDS

The effect of the initial density of a soil (i.e. whether it is loose or dense) on its behaviour when sheared is an important concept in soil mechanics, often explained in the context of the shear box or direct shear test. It is probably the first time that students appreciate that volume changes and shear strength are intrinsically linked, so many struggle with this concept.

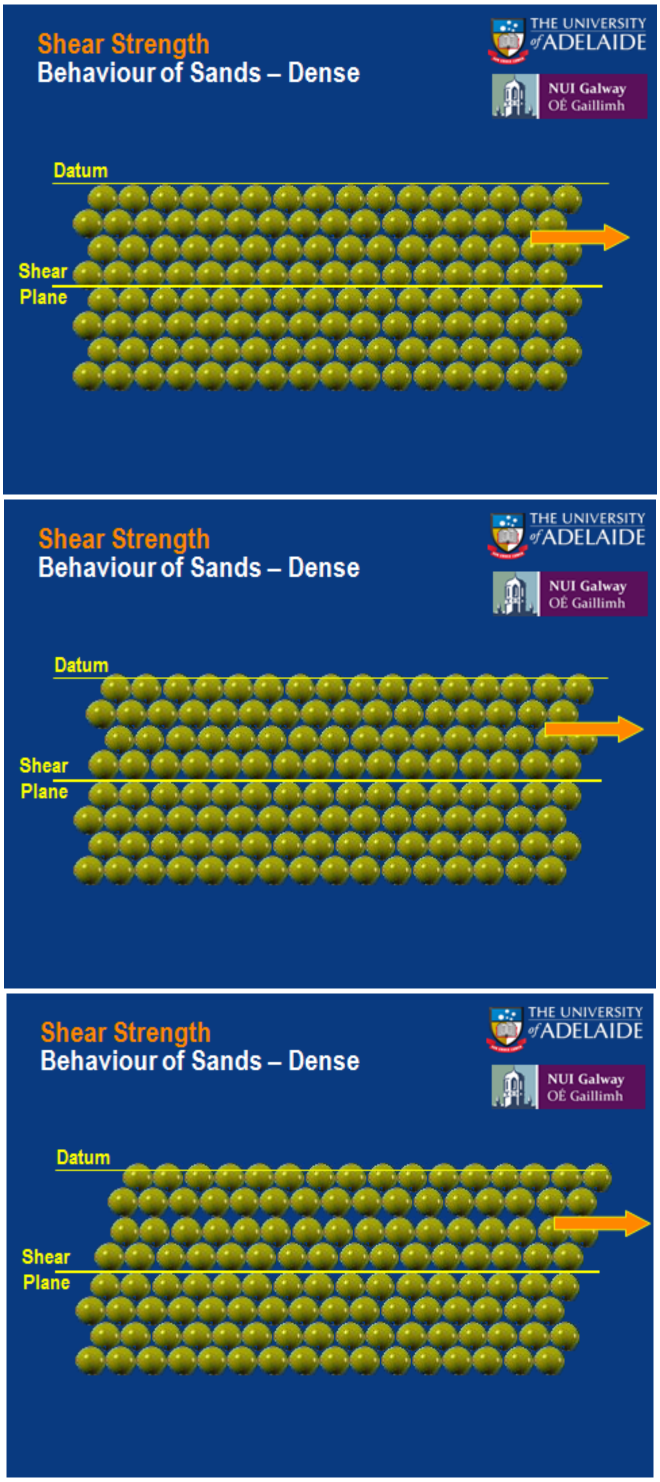


Figure 3a: PowerPoint animated slides using pool balls to explain dilatancy in dense sands

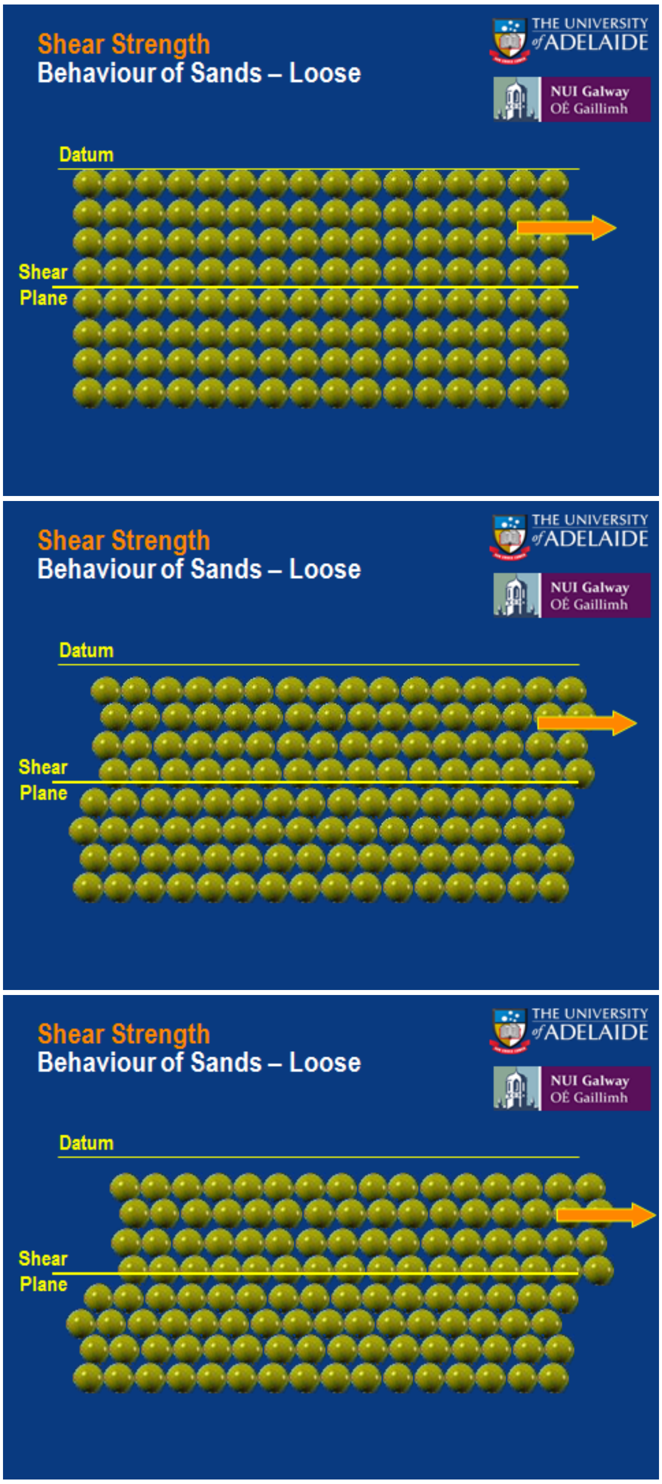


Figure 3b: PowerPoint animated slides using pool balls to explain contraction in loose sands

Students who have played pool or snooker are aware of how to arrange the balls in (i) their tightest possible configuration (i.e. when they are racked together in the triangle at the outset of a game) and (ii) the loosest possible configuration while still maintaining contact, a square grid. As a lead in to the volume change discussion, the students can be asked to extend this to 3-D and calculate the void ratio (e) corresponding to the densest (i.e. rhombic) and the loosest (i.e. cubic) packing. The correct answers are e=0.35 and e=0.92 respectively; Barnes (2000) and Lancellotta (2009) textbooks cover this topic well.

At the University of Adelaide and NUI Galway, a simple series of animated PowerPoint slides are used to explain (in 2-D) why loose soils contract and dense soils dilate (expand) when sheared. In these slides, the individual soil grains are represented as pool balls.

The series of slides used to explain dilatancy in dense soils is shown in Figure 3a. The starting point is assumed for simplicity to be the tightest possible configuration. It is clear that, in order for relative horizontal movement to occur between rows of pool balls, the balls must first of all displace vertically (out of the ‘trough’ in which each is sitting), which gives rise to an overall increase in volume of the soil (gauged relative to the datum line shown). An equivalent set of slides is used to explain contraction in loose soils, assuming for simplicity, the loosest possible starting point (Figure 3b).

Students are advised that the final void ratio at critical state conditions (e_{crit}) is independent of the initial density (whether looser or denser than e_{crit}). These slides can be used as a simple starting point for other models of dilatant behaviour, such as the sawtooth dilatancy model, e.g. Houlsby (1991).

5 STRETCHER (USED IN FORMULA 1 ACCIDENTS) AND EFFECTIVE STRESS

The analogy with sport in this case may be a longer shot than in the previous cases – but the vacuum mattress has been used as a stretcher to remove drivers injured in Formula 1 crashes in the past. Vacuum mattresses are used by emergency personnel as a stretcher over short distances and to immobilise patients, especially in the case of vertebra, pelvis or limb trauma. As shown in Figure 4a, the mattress is a sealed polymer bag (larger than an adult human body) that encloses small polystyrene balls, with a valve, straps and handles. 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 the patient. Air is then withdrawn from the mattress through the valve by means of a hand-operated pump and the valve is then closed. The suction causes the balls to press together and the mattress becomes hard and rigid (Figure 4b).

Figure 4a: Vacuum mattress with hand pump (Source: Wikipedia, 2012)

Figure 4b: Vacuum mattress in use as a stretcher

This example is introduced in lectures after the axiom of effective stress is explained, described by equation [1] for saturated soils:

$$\sigma' = \sigma - u \qquad [1]$$

where σ' is the effective stress, σ is the total stress and u is the pore water pressure. The effective stress does not equate directly to the intergranular pressure, but is a stress which indicates the distribution of load carried by the soil skeleton over the whole area being considered (it cannot be measured).

In the vacuum mattress analogy, σ' is related to the contact loads between the polystyrene balls and u the air pressure inside the mattress. Equation [1] can be used to show that as the air pressure reduces (i.e. u reduces) and σ remains constant, then σ' must increase which gives the mattress its rigidity and strength. This analogy, which can be used in conjunction with the more widely-used vacuum-packed coffee packet analogy, provides a solid frame of reference for students as they grapple with the abstract application of effective stress in soils.

6 EFFECTIVENESS OF SPORTS ANALOGIES

From a class of 66 third-year geotechnical engineering students at the University of Adelaide, Jaksa *et al*. (2009) reports that 91% of the students found that a range of demonstrations used (including two in this paper) improved their learning and understanding of the topics, 89% found them to be engaging and relevant, and 92% believed that they understood the concepts presented in this course.

3rd year Soil Mechanics students at NUI Galway were surveyed specifically about their views on the sporting analogies presented in this paper. The same three questions above were posed here, and the 55 responses on a 5-level Likert scale (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree) averaged 4.3, 4.3 and 4.1 respectively. A selection of specific feedback comments from the NUI Galway students is provided in Table 3.

Table 3: Student feedback comments on the effectiveness of the sporting analogies

"*The analogies helped to make otherwise vague and difficult-to-explain ideas and principles much easier to grasp (in particular the mass-to-surface area ratio analogy that used various forms of sports balls).*"
"*Everybody will have an understanding of some sport, whether it's participating or watching. Therefore sporting analogies can relate the unknown to the known and help students understand the concept more quickly*."
"*The pool ball concept for dense and loose soils was an easy concept to grasp and this worked very well.*"
"*I found the weightlifting example very useful for gaining an understanding on the topic of OCR. Using these analogies is beneficial for studying also as it sticks in the mind which is helpful for exam situations and working through problems.*"
"*I found the visuals easier to comprehend and relating the examples to sports made the subject more interesting and less intimidating*."
"*I think that it is an effective method of engaging students in the topic as most students are involved in sports or can relate to different sports. It makes the topic more relevant to use by using something we know about…the analogies are unusual, they catch the students' attention more and draw them deeper into the subject*."
"*I thought that the sporting analogy used when tackling the overconsolidation ratio was very useful. I had to think about it for a while but when I understood the link between the two, it made it very easy to remember what the overconsolidation ratio was all about.*"
"The visual images also help to keep the sports references fresh in my mind and from there my understanding of some concepts."

7 CONCLUSION

In this paper, the authors have shared some simple analogies between sport and soil mechanics concepts used in teaching at the University of Adelaide and NUI Galway. Weightlifting is used to explain OCR and stress history, various sports balls are used to explain the concept of specific surface area, pool/snooker balls are used to explain dilatancy and contraction in sands, and a vacuum mattress stretcher is presented as a practical application of the effective stress principle.

Experience at both universities suggests that analogies and demonstrations in general are effective, and that the sporting analogies presented herein are engaging and succeed in conveying certain concepts. This paper may also serve as a fun reference document for students in introductory soil mechanics courses elsewhere, as a component of the multi-faceted approach to geotechnical education advocated by Jaksa (2008).

REFERENCES

Airey, D.W. 2008. A project based approach to teaching geotechnical engineering, *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constanza, Romania, pp. 357-362

Atkinson, J.A. 2007. The mechanics of soils and foundations, Spon Text, 2nd edition.

Atkinson, J.A. 2008. What should geotechnical engineers be able to do and how should they acquire these skills? *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constanza, Romania, pp. 3-8

Barnes, G. 2000. Soil Mechanics Principles and Practice, Macmillan Press, 2nd Ed.

Dagher, Z.R. 1995. Analysis of analogies used by science teachers, Journal of Research In Science Teaching, Vol. 32, Issue 3, pp. 259-270.

Donnelly, C.M. and McDaniel, M.A. 1993. Use of analogy in learning scientific concepts, *Journal of Experimental Psychology: Learning, Memory and Cognition*, Vol. 19, No. 4, pp. 975-987.

Felder, R.M. and Silverman, L.K. 1988. Learning and teaching styles in engineering education, *Engineering Education*, Vol. 78, No. 7, pp. 674-681.

Heywood, D. and Parker, J. 2010. The role of analogies in learning, *The Pedagogy of Physical Science. Contemporary Trends and Issues in Science Education*, Vol. 38, pp. 39-64

Houlsby, G.T. 1991. How the dilatancy of soils affects their behaviour, *Proceedings of the 10th ECSMGE*, Florence, Italy.

Jaksa, M.B. 2008. A multi-faceted approach to geo-engineering education, *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constanza, Romania, pp. 493-497.

Jaksa, M.B., Ho, K. and Woodward, M.A. 2009. Keynote Lecture: Management, Training and Education in Geotechnical Engineering, *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, Alexandria, Egypt, Vol. 4, pp. 3136-3170.

McCabe, B.A. and Phillips, D.T. 2008. Is geotechnical education meeting 21st century industry demands? The Irish position, *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constanza, Romania, pp. 493-497.

Orr, T.L.L. and Pantazidou, M. 2012. Case histories in geo-engineering education, *Proceedings of Shaking the Foundations of Geo-engineering Education*, Galway, Ireland.

Phillips, D.T. 2008. Benefits of case-based instruction in undergraduate education, *Proceedings of the 6th International Conference on Case Histories in Geotechnical Education*, Arlington, VA.

Lancellotta, R. 2009. Geotechnical Engineering, Spon Text, 2nd Ed.

Wikipedia 2012. Vacuum mattress (accessed January 2012). http://en.wikipedia.org/wiki/Vacuum_mattress