UnSaLuDo: The development of an educational board game on unsaturated soil mechanics

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Abstract. Non-conventional tools of teaching are effective in delivering deep learning of scientific facts as well as skills associated with scientific disciplines. A well-known method to promote student engagement and learning in general is the use of games in classrooms. Games can provide a flexible option that could engage students, create active learning experiences, and enable them to experiment in safe playful environments. This paper presents UnSaLuDo, a board game developed by the GeoFUN group. The goal was to develop a tool that enables students to experience fun and integrational activities in a classroom setting while learning complex scientific targeted threshold concepts related to unsaturated soil mechanics. The topics covered by UnSaLuDo included fundamental concepts of cohesion and adhesion in liquids, surface tension, contact angle and capillary rise; water retention and water flow in unsaturated soils; volume change, deformation, and shear strength of unsaturated soils. This paper provides background information on the motivation for the development of the board game and an overview of the topics covered. The paper also presents all the components of the board game developed and suggests approaches for how it can be incorporated into geotechnics courses.

1 Introduction

Despite the recognised importance and relevance of unsaturated soil mechanics to routine geotechnical engineering practice, the incorporation of unsaturated soil mechanics concepts in undergraduate curriculum remains a worldwide challenge. Part of this challenge is associated with the theoretical and experimental complexity of the subject. In the last couple of decades increasing interest in including unsaturated soil mechanics fundamentals into engineering practice has been observed [1,2,11,12,3–10]. However, although researchers have been putting more effort towards bridging this gap, lecturers still find it difficult to teach the subject within the boundaries of geotechnics modules. This then creates a challenge to the industry that is now aware of the need to use unsaturated soil principles in practice but finds hardly any newly graduated student with understanding of the subject.

According to a survey [13] carried out in the US, geotechnical engineering faculties are still reluctant to teach unsaturated soils because they believe it will be difficult to integrate additional content into an already full semester. This challenge could become less of a burden if teaching resources, and experiences created by different geotechnical engineering faculties on the subject are shared with the unsaturated soil mechanics community.

In this context, this paper discusses the development of UnSaLuDo, a board game designed to provide lecturers with opportunities to assess their students' familiarity with the principles of unsaturated soils. UnSaLuDo is based on the popular Ludo, patented in England in 1896 [14].

The topics covered by UnSaLuDo were highly influenced by the content of a module offered at University of Strathclyde (UK) to MEng and MSc students formerly known as “Slopes and Walls (with Mechanics of Unsaturated Soils)” (currently “Geotechnics of Unsaturated Soils”) that has also influenced the unsaturated soil mechanics content of the “Advanced Geomechanics” module offered to MSc students at Newcastle University (UK). The subjects covered by UnSaLuDo includes fundamental concepts of cohesion and adhesion in liquids, surface tension, contact angle and capillary rise; water retention and water flow in unsaturated soils; volume change, deformation, and shear strength of unsaturated soils.

This paper presents UnSaLuDo, an educational board game developed by GeoFUN group. Firstly, a brief overview of the topics covered by UnSaLuDo is presented. Then, all the components of the board game developed and suggestions of approaches for how it can be incorporated into geotechnics modules are discussed.

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2 UnSaLuDo content

2.1 Fundamental concepts

Before unsaturated soils can be discussed, the fundamental physics concepts of surface tension, cohesion and adhesion in liquids need to be introduced.

Cohesion is the attraction force between molecules of the same type, while adhesion is the attraction force between molecules of different type [15] Video demonstrations from NASAeClips [16] of these two forces at the International Space Station can help students master the concepts at no time.

Surface tension is the ability of a liquid surface to operate like a stretched elastic membrane [17]. Abstract concepts can be easier understood with the help of visual aid and real-life examples. Surface tension concept is illustrated and explained at a video produced by the BBC Earth Lab [18] that explores the capacity of the water strider to "walk on water".

Once these three concepts are well understood, they can be brought back into perspective to the context of capillary tubes, the analogy used in unsaturated soil mechanics to explain the soil-water retention behaviour.

In a capillary tube the interface between air and water curves in the proximity of a solid surface to form a meniscus (Fig. 1). Typically, in soils, this interface is concave towards the air with a contact angle smaller than 90° with the solid surface, since adhesive forces between solid and water outweigh cohesive forces in the water. Menisci concave on the air side generate water pressures lower than the air pressure.

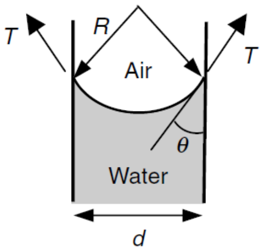

Fig. 1. Negative water pressure generated by meniscus concave on the air side (after [3])

By considering the vertical force equilibrium of the air–water interface, the water pressure at the back of the meniscus can be calculated as:

$$u_w - u_a = -\frac{4T\cos\theta}{d} = -\frac{2T}{R} \qquad (1)$$

where u_w is the water pressure at the back of the meniscus, u_a is the air pressure, T is the surface tension, θ is the contact angle, d is the diameter of the capillary tube and R the radius of curvature of the interface. If the contact angle is lower than 90°, the gauge water pressure $u_w - u_a$ becomes negative.

2.2 Water retention

A soil deposit can be subdivided into three regions: one below the phreatic line and two above. The zone below the phreatic line is known as the saturated zone with positive pore-water pressure. In the area immediately above the water table, known as the capillary zone, the soil is still saturated, but pore water pressure is negative. The area above the capillary zone is characterised by soil that is no longer saturated, a region known as unsaturated. In this latter zone the pore-water pressure is also negative [9].

A critical hydraulic property of the soil is the soil water retention curve. This property characterises the relationship between saturation and the pore water pressure, or suction of the soil [9]. This curve describes the different saturation states of the soil (Fig. 2), and it can be explained using the analogy of capillary systems.

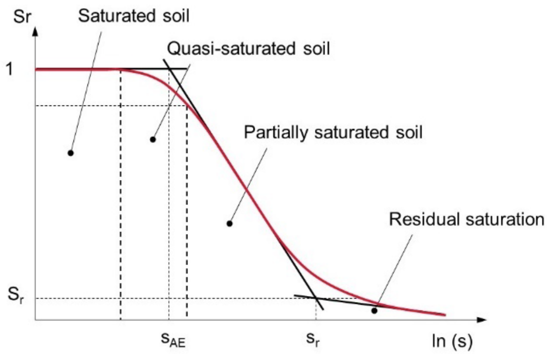

Fig. 2. Typical soil-water retention curve, where *s* is suction, and *Sr* is degree of saturation

If a "saturated" soil (degree of saturation, Sr = 1) undergoes desaturation, initially menisci are formed at the surface without any displacement of the air-water-solid junction. When desaturation advances, the interface decreases its curvature and the thermodynamic potential increase too, i.e., suction increases causing shrinkage of the soil (or expansion of undissolved air cavities) and the degree of saturation decreases in the process, characterising the "quasi-saturated" state of the soil [3,10,19]. When this stage starts, the curvature of the water interface reaches its limit, the menisci then recede into the soil and the air enters the soil (suction at air entry value, s_{AE}). From this moment water and air are continuous in the pore spaces, which characterises the "partially saturated" stage. Finally, the more air enters the soil, more discontinuous the water is in the pore space, which characterises the "residual" state of the soil saturation [3,10,19].

The relationship between degree of saturation and suction is hysteretic, that is, the water retention behaviour of a soil dried from saturated state ("main drying") is different from that of a soil wetted from dry state ("main wetting"). The "main drying" and "main wetting" curves mark out the domain of possible attainable states (hysteresis domain). The main reason for hysteresis is the so-called ink-bottle effect, which refers to the narrow point of contact between large cavities of adjoining pores [3,10,19].

2.3 Water flow

The capillary tubes analogy is also useful to introduce the hydraulic conductivity of unsaturated soil. The flow velocity, v, in a saturated capillary tube of diameter d is given by:

$$v = \left[\frac{g}{2\eta} \cdot \frac{d^2}{16} \cdot n\right] . i \tag{2}$$

where g is the acceleration of gravity, η is the kinematic viscosity, n is the porosity and i is the hydraulic gradient.

For the case of water flow in an unsaturated capillary tube (Fig. 3) the equation known as the Kozeny–Carman equation can be written:

$$v = \left[\frac{g}{2\eta} \cdot \frac{1}{S_o^2} \cdot \frac{e^3}{1+e} \cdot Sr^3\right] . i \tag{3}$$

where S_o is the specific surface, and e is the void ratio. The unsaturated hydraulic conductivity can, therefore, be written as:

$$k = \left[\frac{g}{2\eta} \cdot \frac{1}{S_o^2} \cdot \frac{e^3}{1+e}\right] . Sr^3 = k_{sat} . Sr^3 \tag{4}$$

where k_{sat} is the saturated hydraulic conductivity.

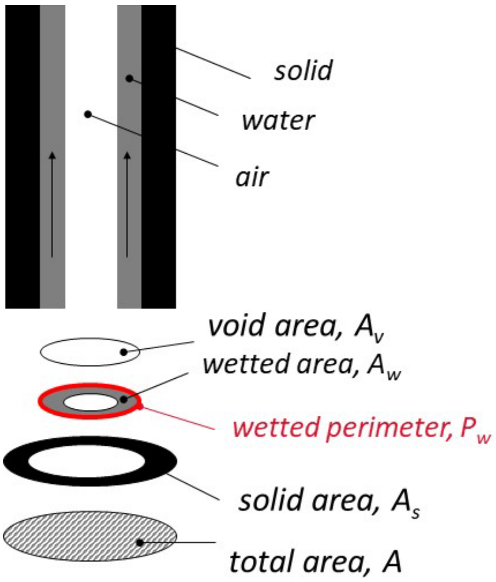

Fig. 3. Flow in unsaturated capillary tube (after [3])

Water flow through unsaturated soils is governed by the same flow law as through saturated soils (i.e., Darcy's law). The hydraulic conductivity governing the water flow, in saturated soils is constant, while in the unsaturated state, the hydraulic conductivity is a function of suction, water content, or some other variable for unsaturated soils [9].

2.4 Shear strength

In the saturated soils, the shear strength, can be written as [20]:

$$\tau = c' + (\sigma - u_w) . tan\phi' \tag{5}$$

where c' is the effective cohesion intercept, σ is the total normal stress to the failure plane and ϕ' is the saturated angle of shearing resistance.

The shear strength criteria for soils subjected to suction can be written as follows [21–26]:

$$\tau = c' + \sigma . tan\phi' + f(s, Sr) . tan\phi' \tag{6}$$

where *f(s,Sr)* is a function of suction and degree of saturation, that represents the contribution of suction and degree of saturation to the shear strength of the soil, $\Delta\tau_{s,Sr}$.

Tarantino and El Mountassir [27] showed that for sandy and silty soils the simplest assumption for this function is supported by experimental evidence in which:

$$f(s, Sr) = s . Sr \tag{7}$$

However, for clayey soils Eq. (7) overpredicts the shear strength of the soil. Tarantino and El Mountassir [27], then discussed that the failure criterion for clayey soils should be written by considering a different function for *f(s,Sr)* as suggested by Vanapalli et al.[24]:

$$f(s, Sr) = s . Sr^k \tag{8}$$

where k is a constant.

The shear strength criterion given by Eq. (8) is difficult to use in engineering practice because the parameter k is soil-specific and requires tests on unsaturated samples to be carried out [27]. However, a simplified, more conservative, shear strength criterion, can be developed making use of information more readily available or easier to estimate. The contribution of suction to the shear strength of the soil, $\Delta\tau_{suction}$, can be written as:

$$\Delta\tau_{suction} = s . tan\phi' \qquad s \leq s_{AEV}$$
$$\Delta\tau_{suction} = s_{AE} . tan\phi' \qquad s > s_{AEV} \tag{9}$$

where s is the suction.

The inter-particle stresses at the saturated and meniscus contacts can help explain the contribution of suction to the shear strength of the soil. Fig. 4 shows typical evolution of Δτ, the difference between the shear strength τ and the shear strength at zero suction, σ.tanϕ', as suction increases and degree of saturation decreases [28–31].

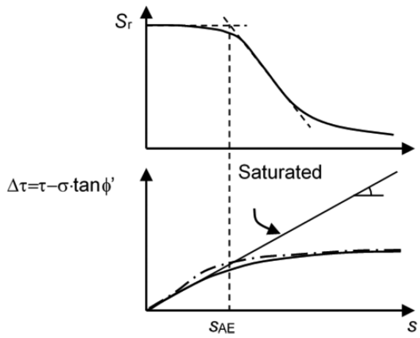

Fig. 4. Contribution of suction to shear strength (source [19])

2.5 Volumetric behaviour

Soils, even non-collapsible ones, can undergo deformations due to changes in water content or water pressure [10]. Fig. 5a shows the relationship between void ratio and suction for a soil sample subjected to drying. An increase in suction causes an increase in σ-u_w in the saturated portion of the sample and, in turn, a decrease in volume takes place in this portion of the sample ($\Delta V<0$). Meanwhile, an increase in suction induces a decrease in degree of saturation and, as a result, new menisci form. As the saturated portion retracts, the decrease in volume of the saturated part affects less and less the overall volume change. At the same time, the number of menisci increase, which hinders particle slip and, in turn, decrease in volume. As suction increases, void ratio tends to level off and the unsaturated soil is said to attain the shrinkage limit [32].

Fig. 5b shows the relationship between void ratio and suction for a soil sample subjected to wetting. A decrease in suction causes a decrease in σ-u_w in the saturated portion of the sample and, in turn, an increase in volume takes place in this portion of the sample ($\Delta V>0$). A decrease in suction induces an increase in degree of saturation and, as a result, menisci tend to disappear. As the saturated portion expands, the increase in volume of the saturated part affects more and more the overall volume change. At the same time, menisci are progressively removed, and their effect of stabilising contact tend to vanish. Then if the sample is subjected to a relatively high total stress, the structure tends to collapse if loaded. As suction decreases, void ratio initially tends to increase then abruptly decrease as the soil structure collapses. However, if the sample is subjected to a low total stress, collapse is not observed, as indicated in Fig. 5b [19].

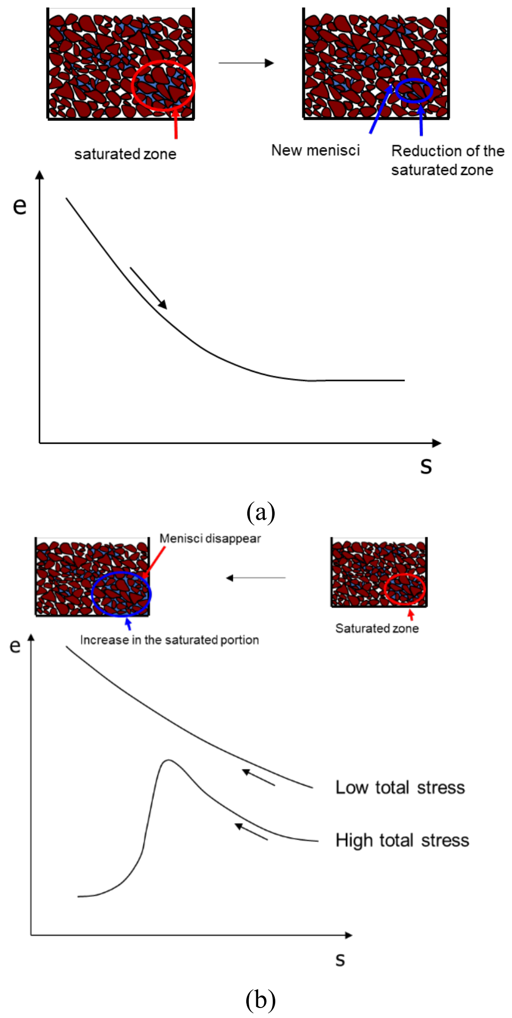

Fig. 5. Relationship between void ratio and suction for soil sample upon (a) drying and (b) wetting

3 UnSaLuDo

3.1 Game rules

3.1.1 Game components and number of players

The game is composed of the Board, 8 pawns (2 for each player), "Special" and "Movement" Cards. It can be played by 2 to 4 players.

3.1.2 Setting up the board

Each player chooses one of the four colours (green, pink, yellow, or blue) and places the two pawns of that colour in the corresponding starting 'elevated ground level'.

The pawns must remain in the 'elevated ground level' until they are brought into play. While the pawns are in the 'elevated ground level' they are not yet in play.

3.1.3 How to win

The first player to move all two pawns to the home triangle at the centre of the board wins.

3.1.4 How to put pawns in play

Players must decide among themselves which player will start. The order of play will proceed clockwise from the player who goes first.

To get a pawn into the board, each player must correctly answer a card from the "Special" deck on their turn. If the starting player does not answer the card correctly, then the next player takes their turn. If the player does answer the card correctly, he/she brings a pawn onto the board and places it on the start space.

3.1.5 How to play

In each turn, the player decides which pawn to move (if they are both in play). A pawn simply moves in a clockwise direction around the track when the player correctly answers a card.

There are two types of card decks: "Movement" and "Special".

"Movement" cards are standard cards that allow the players to move their pawns on the board. The number of spaces of movement is defined by the card, if the question is answered correctly. There is no punishment for the player that answers the "Movement" cards incorrectly.

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"Special" cards can be requested at any time if the player wants to take their pawn in play. It can also be requested every three rounds to double the reward in the "Movement" card if the player answers correctly the question asked. However, if the players answer the "Special" card incorrectly, his/her pawn goes back to the 'elevated ground level'. Pawns can only enter the home triangle if the player answers a "Special" card correctly. "Special" cards can be also requested to protect a pawn, they can be used every three rounds.

A player can capture an opponent's pawn any time he/she lands on the same space one of their pawns is on. If a player lands on another player's pawn space, the opponent must take the pawn off of the board and move it back to the 'elevated ground level'.

Pawns that are currently under the protection of the "Special" card cannot be captured; the effect is valid only if the pawn does not move. Arrow and entrance spaces are safe zones.

3.2 Game design

The board is presented in Fig. 6. The 'elevated ground level' are the four soil profiles with green grass on the outer four courners of the board (Fig. 6). The 'arrow' spaces are represented by light yellow spaces with a rock and an arrow in Fig. 6, while the entrance spaces are the coloured (pink, yellow, green and blue) spaces with a vegetated soil drawn on it (Fig. 6). A few of the essential equations related to the topics covered are spread out on the board.

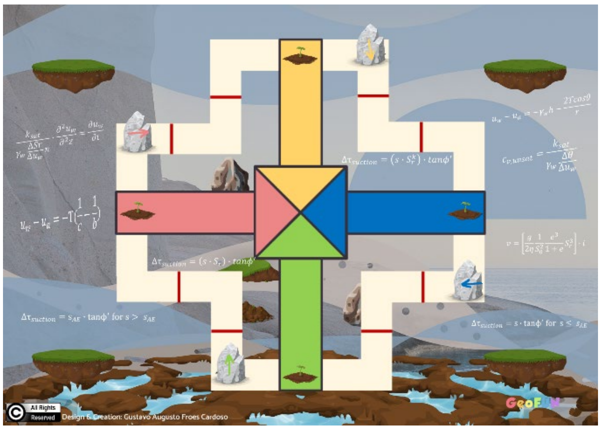

Fig. 6. The board

3.3 Sample cards

Both "Movement" and "Special" card sets have multiple-choice, True or False and open questions. Fig. 7 illustrates the design of the "Movement" card deck for the case of multiple-choice type of questions. "Special" cards are made up of more complex questions. Some of the content of the cards are presented here.

3.3.1 Movement cards

M.1. A capillary tube (600mm long) is described by two different radii (0.15mm and 0.05mm). The larger radius is 200mm long located in the middle of the tube. If the tube is initially filled with water, where will the water level in the tube be if it is put in contact with a water reservoir (in mm)?

a) 192 b) 200 c) 576 d) 600

Answer: C – The capillary rise associated with the diameter of 0.15 is 192mm while the one associated with a diameter of 0.05mm is 576mm. The section of the tube with 0.15mm diameter is below 576mm therefore, the water in the tube behaves as if the whole tube has a diameter of 0.05mm and the water level lowers until it reaches a height of 576mm from the water surface.

M.2. What is the water pressure generated by the meniscus for the case of a capillary tube of radius r=1 μm (assume T=0.072 N/m, θ=0° and u_a = 100kPa)?

a) -39kPa b) -44 kPa c) -48kPa d) -55kPa

Answer: B

$$u_w - 100 = -\frac{4 \times 0.072 \times cos0}{2 \times 10^{-6}} \therefore u_w = -44kPa$$

M.3. Between sand, silt, and clay, which one would have the lowest air entry value?

a) Sand b) Silt c) Clay d) All of them could have the same air entry value

Answer: A. Sand has the largest pores, therefore it has the lowest air entry value.

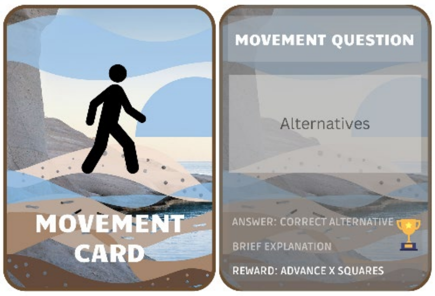

Fig. 7. "Movement" cards design

3.3.2 Special cards

S.1. Which of the following describes surface tension in water?

a) Surface tension occurs due to ionic bonding.

b) Surface tension is caused by water molecules repelling one another.

c) Surface tension allows water to support small objects if they are placed carefully on its surface.

d) Surface tension of water is weakened by hydrogen bonding.

Answer: C - Surface tension is the tendency of a liquid's surface to resist rupture when placed under tension or stress. If a small object is placed carefully on its surface, the tension created by the hydrogen bonds in the water can often prevent the object from sinking.

S.2. How can the suction at air entry value, s_{AE}, of a soil be obtained if one has the SWRC of the soil?

Answer: s_{AE} value is obtained graphically by intersecting the horizontal line at degree of saturation equal to 1 with the line tangent to the curve at the inflection point.

S.3. Suction is maximum when angle of contact, θ is:
a) 0 b) 90 c) 60 d) 45
Answer: A. Suction ∝ cos θ

4 Suggestions for using UnSaLuDo in lectures

Since UnSaLuDo's content was based on unsaturated soil topics taught in modules at University of Strathclyde and Newcastle University and these in turn follow the approach proposed by Tarantino and Di Donna [3], it is sensible that lecturers introduce the content of the paper before attempting to use UnSaLuDo in their classrooms.

For that, flipped classroom activities, followed by other active learning activities, such as peer instruction, group discussions and problem-based lectures seem appropriate to introduce the content of the paper/board game. These activities can be adjusted to be delivered within 6 to 15 lecture hours, to fit into specific curriculum requirements.

Written materials for lecturers to support the use of UnSaLuDo as well as a printable pdf of the board game itself are available on reasonable request.

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