Determination of the Soil Water Retention Curve Using the Flow Pump

Determinação da Curva de Retenção de Água em Solos Utilizando a Bomba de Fluxo

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Abstract

Reliable measurements of the Soil Water Retention Curve, SWRC, are necessary for solving unsaturated flow problems. In this sense, a method to obtain the SWRC of a silty sand using a flow pump, as well as details about procedures and some results, are herein presented. The overall conclusion is that the new method is very convenient, fully automated, and produces reliable results in a fast and easy way, making the technique very promising.

keywords: Soil water retention curve, flow pump, unsaturated flow, laboratory testing.

Resumo

A curva de retenção de água no solo é uma função característica do solo necessária para a resolução de problemas geotécnicos com fluxo em solos não saturados. Os ensaios, para determinação direta dessa propriedade, são, em geral, custosos e demorados, fazendo com que seja muito difundido o uso de bancos de dados de curvas de retenção para diferentes tipos de solos, classificadas a partir de propriedades-índice, tais como granulometria e densidades. Esse expediente, ainda que possível para estudos preliminares, não se apresenta suficiente para um problema específico. Nesse sentido, apresenta-se um método para obtenção da curva de retenção em laboratório com o auxílio da bomba de fluxo. Foi feita a implantação de um sistema para a realização desse ensaio, que, juntamente com procedimentos e alguns resultados, tem os detalhes descritos no artigo. A avaliação geral da técnica foi a mais positiva possível, fazendo crer aos autores que o uso a bomba de fluxo, nessa aplicação, seja bastante promissor.

Palavras-chave: *curva de retenção de água em solos, bomba de fluxo, fluxo não saturado, ensaio de laboratório.*

1. Introduction

In Classic Soil Mechanics, soil is modeled as a two-phase system: soil-air and soil-water, or their equivalents, dry soil and saturated soil (Terzaghi, 1936). Recently, with the raise of environmental awareness regarding contaminant transport, there has been a need to address flow and shear strength in unsaturated soils.

So, a three-phase model for soil, that is, a soil with air besides water in its pores was used. This extension of knowledge gave rise to a new discipline called Unsaturated Soil Mechanics.

An important development for unsaturated flow studies can be expressed by Equation (1), known as the Richard´s equation.

$$\frac{\partial}{\partial x}\left[K(\psi)\frac{\partial\psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(\psi)\frac{\partial\psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z}+1\right)\right]=C(\psi)\frac{\partial\psi}{\partial t} \quad (1)$$

where x, y, z are spatial independent variables, t is time, ψ is the pressure head, $k(\psi)$ is the hydraulic conductivity function, and $C(\psi)$ the specific moisture capacity, defined in the soil water retention curve (SWRC) by Equation (2) (FREEZE & CHERRY, 1979).

$$C(\psi)\frac{d\theta}{d\psi} \quad (2)$$

The SWRC, also called soil water characteristic curve, describes the relationship between the soil matrix suction (expressed in terms of head or pressure) and the soil volumetric water content, θ, or the degree of saturation, *S*.

Besides usual tests for SWRC determination (filter paper, pressure plate, resistance/capacitance sensors and others) alternative techniques have been developed, such as the procedures presented by Znidarcic *et al*. (1991), Manna *et al*. (1993), Wildenschild *et al*. (1997), Hwang (2002) and Lee (2011). In all of these publications, the authors used a flow pump to obtain the SWRC.

The flow pump is used to establish a water flux through a soil specimen at an imposed flow rate, establishing a transient or permanent seepage regime. The equipment is operated in both withdrawal mode and infusion mode, allowing capture of the intrinsic hysteresis aspect of the SWRC.

During the test, the flow rate and the flow pump working time information is obtained. Moreover, the soil suction, existing inside the specimen, is also known through a differential pressure transducer, connected to the specimen top (air) and bottom (water). Then, the SWRC is obtained through recorded data reduction.

This flow pump technique shows several advantages when compared to usual tests to obtain the SWRC. For instance, the same specimen is used to obtain both drying and wetting soil water retention curves. Another important advantage is that the test time can be shortened to just a few days. In addition, the whole operation can be automated as shown in this paper.

In Brazil, the use of a flow pump to obtain other soil properties, such as soft soil consolidation relationships (hydraulic consolidation test or seepage induced consolidation test) was well established by research carried out by Botelho (2002), Lima (2009) and Oliveira-Filho & Menezes (2012). These studies facilitated the extension of the use of the flow pump in geotechnical engineering.

The objectives of this research were to implement a system to obtain the SWRC using the methodology developed by Lee (2011), to verify its applicability for mining tailings, and also to contribute to the spread of this promising technique in Brazil.

2. Material and methods

The flow pump system (FPS) developed by Lee (2011) to determine the SWRC was implemented in the Mining Residue Laboratory at Federal University of Ouro Preto (UFOP). Figure 1 shows the FPS built at UFOP.

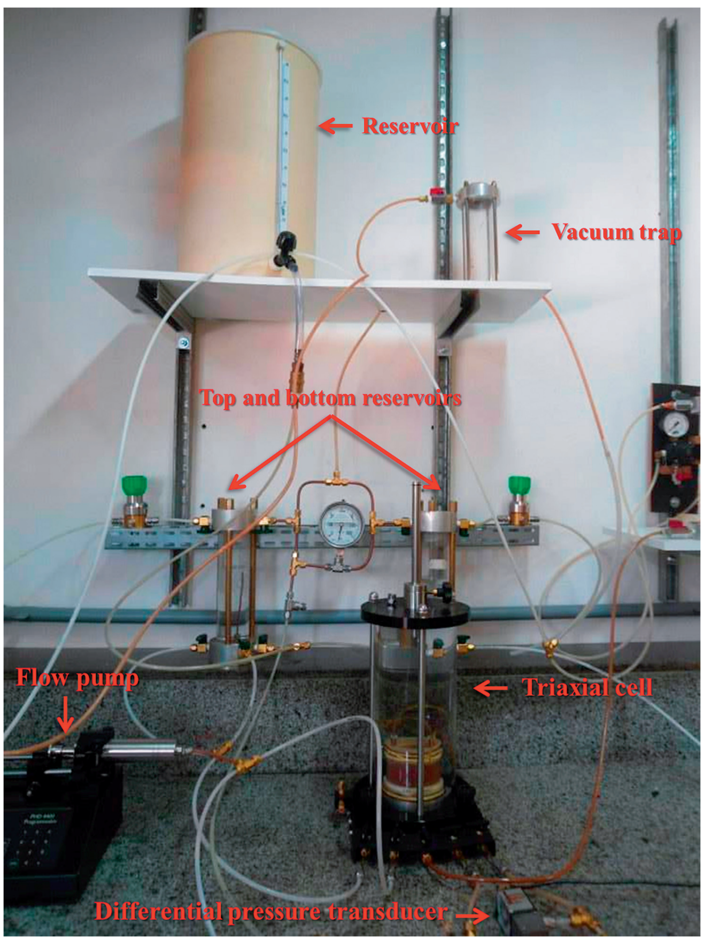

Figure 1
Flow pump system at
Mining Residue laboratory, UFOP.

The FPS consists of a modified triaxial cell, an air pressure and vacuum system with gauges, a differential pressure transducer, an automated test control and data acquisition software and hardware, and a flow pump. The flow pump used in the experiments was a PHD 4400 model made by Harvard Apparatus Company.

The SWRC test with the flow pump is divided in water withdrawing stages (drainage cycle) or infusion stages (infiltration cycle), which causes suction to increase or decrease within the soil specimen. This is followed by equilibrium stages to generate suction and volumetric water content equalization.

In the beginning of the test, the pump is in the withdrawal mode, causing a steady increase in suction within the specimen. When the suction reaches a target level (target suction), the pump is halted and the suction drops until it reaches a limit value (threshold suction). According to McCartney & Znidarcic (2010), the difference between these two values should be 1 kPa for accuracy. Having reached the threshold value, the pump is automatically restarted by the control system, which causes suction to increase again until it reaches the target value (target suction), when the pump is halted once more. This process is automatically repeated many times, creating an equilibrium stage, until a certain time limit for suction decay is reached, 5000 seconds in this case.

After the end of the equilibrium stage, the flow pump is restarted, beginning a new cycle of water withdrawal. Consequently, there is an increase in suction until the next target suction is reached. At this time, the pump is halted and a new equilibrium stage starts. This procedure is repeated for several target suctions. The last target suction in equilibrium is the first stage of the SWRC inverse way, now with the pump in the infusion mode (infiltration cycle). The following steps are in water infusion and equilibrium stages within the specimen. During the infusion phase, the suction decreases as water flows into the specimen.

Target suction values are defined within the suction range of interest in the drainage stage. They are usually repeated in the infusion phase of the test. Figure 2 schematically illustrates the test steps and the equalization stages within the specimen as suggested by Lee (2011).

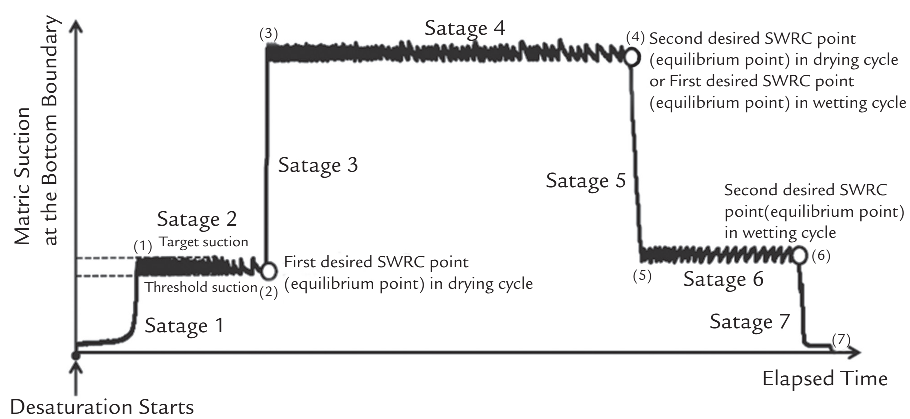

Figure 2
Schematic test results for the SWRC using the flow pump (Lee, 2011).

In the flow pump test, the axis translation technique is used to produce suction. Thus, when the pump is operating in withdrawal or infusion mode, the suction is measured by the pressure differential transducer, taking the pressure difference between the air pressure at the specimen top and the water pressure at the specimen bottom. The air pressure is the same backpressure used in the specimen saturation before the test starts, and it remains constant during the entire test. The suction increases in the drainage cycle and decreases in the infiltration cycle. A data acquisition system is used to store suction values developed within the specimen during the test.

The reference apparent velocity (Darcian) for testing should be slightly higher than the specimen saturated hydraulic conductivity (k_{sat}), which is obtained before the SWRC test, using the same FPS. If the velocity is lower than k_{sat} the test will last quite a long time. If the velocity is much higher than ksat, there will be an impact on precision to reach the target and the threshold suctions.

The material used to prepare the test specimen was silty sand, classified as SM (Unified Soil Classification System, USCS), passing through #4 sieve (4.8 mm). Specimen dimensions were 72x40 mm (height x diameter). Figure 3 shows the gradation curve and specific gravity corresponding to this material.

Specimen preparation and saturation were carried out according to the procedures proposed by Hwang (2002). A soil specimen is placed in the triaxial cell on a saturated ceramic stone with an air entry value of 1 bar (100 kPa) and a diameter slightly larger than the specimen diameter to prevent the flow of air from the specimen to the measuring system, which needs hydraulic continuity and complete saturation. The ceramic stone sits on a saturated filtering porous stone, placed on the triaxial pedestal. A filtering porous stone and a triaxial specimen head are placed on the specimen top. Filter paper is also placed at both ends of the specimen to prevent impregnation of fine particles in the ceramic and porous stones. The triaxial cell is then closed and filled with water, as the confining fluid.

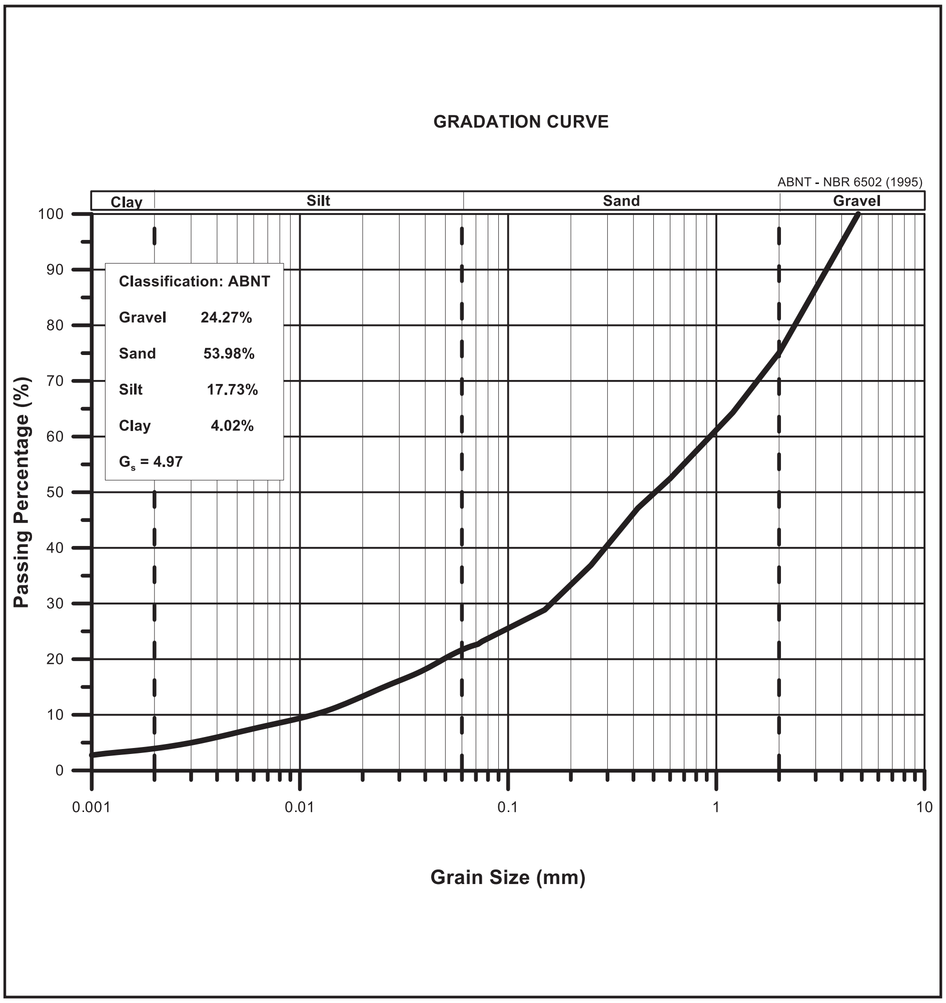

Figure 3
Specimen gradation
curve and specific gravity.

The specimen initial saturation is obtained by percolation of distilled and de-aired water using vacuum applied in the top drainage line.

Saturation is later completed by backpressure.

To ensure specimen saturation, B parameter test is performed according to Equation (3).

$$B = \frac{\Delta u}{\Delta \delta_3} \tag{3}$$

where B is the Skempton´s pore pressure parameter, Δu the water pore pressure change in undrained conditions, and $\Delta\sigma_3$ the pressure increase in the confining fluid of the triaxial cell.

Existing suctions within the specimen during the test and time periods are recorded during the test when the pump is operating (in withdrawal or infusion modes) or is halted.

This last information is used to determine the amount of water remaining in the specimen at any time.

From these records, the average degree of saturation during the test is evaluated (Equation (4))

$$S = S_0 \pm \Delta S = S_0 \pm \frac{Q\Delta t}{nV} \tag{4}$$

where S = degree of saturation at any time; S_o = initial degree of saturation, usually equal to 1;
Q = pump flow rate;
Δt = accumulated time of pump operation; n = porosity; V = total volume.

With suction and degree of saturation pair values, SWRC data points are fitted according to mathematical or predicting models such as Brooks & Corey (1964) and van Genuchten (1980).

3. Results and discussions

Testing to obtain SWRC started with B parameter test, as shown in Figure 4a.

Cell pressure was increased by 40 kPa and the specimen water pore pressure increased the same amount. With a saturated specimen, the constant flow rate permeability test was then conducted with the same specimen using FPS to obtain ksat. From permeability test results, it was found that the average ksat equals to $2.53\text{x}10^{-7}$ m/s (Figure 4b).

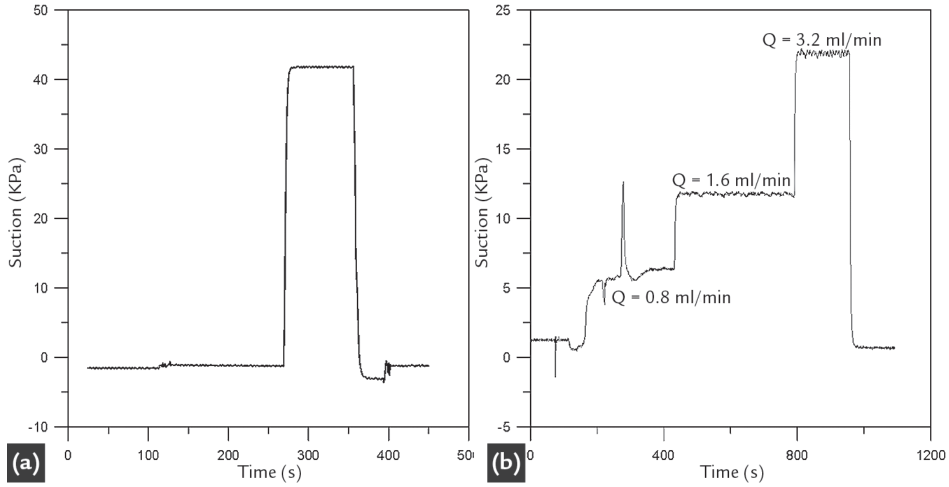

Figure 4
Preliminary results:
a) B Parameter test results;
b) Constant flow
rate test results to obtain ksat.

The SWRC test was performed by imposing a flow rate of 0.12 ml/min, which corresponds to the double of k_{sat} value. The chosen suction target levels were 20, 40, 70 and 90 kPa. Test results are shown in Figure 5.

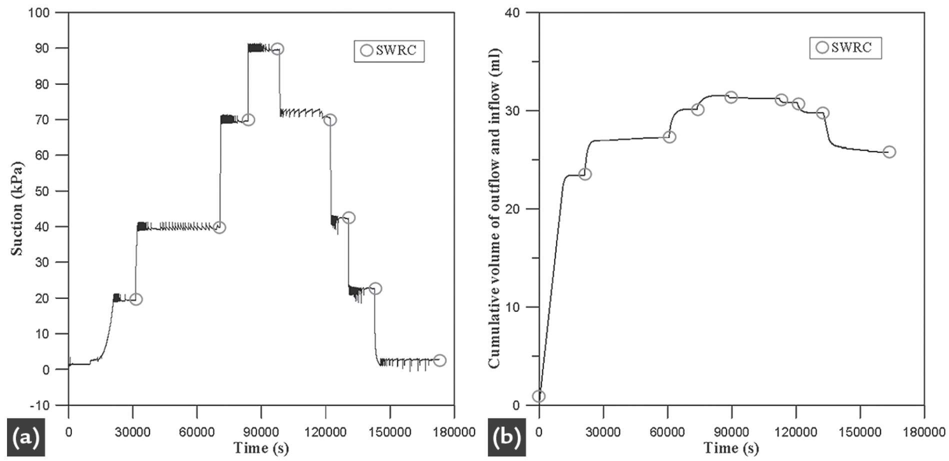

Figure 5
Test results to obtain
the SWRC using the FPS.

Results shown in Figure 5 can be combined to produce the suction versus average volumetric water content, shown in Figure 6.

The circled points are the actual data points of the SWRC.

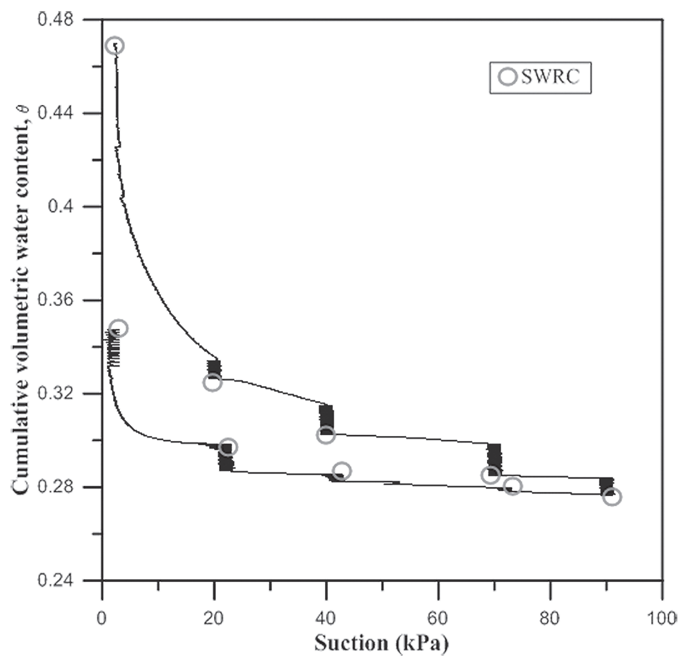

Figure 6
Suction – average
volumetric water content curve.

Test data were then fitted to the mathematical models of Brooks & Corey (1964) and van Genuchten (1980) as shown in Figure 7.

This figure demonstrates that both models provide an excellent fit to the experimental data over the entire range.

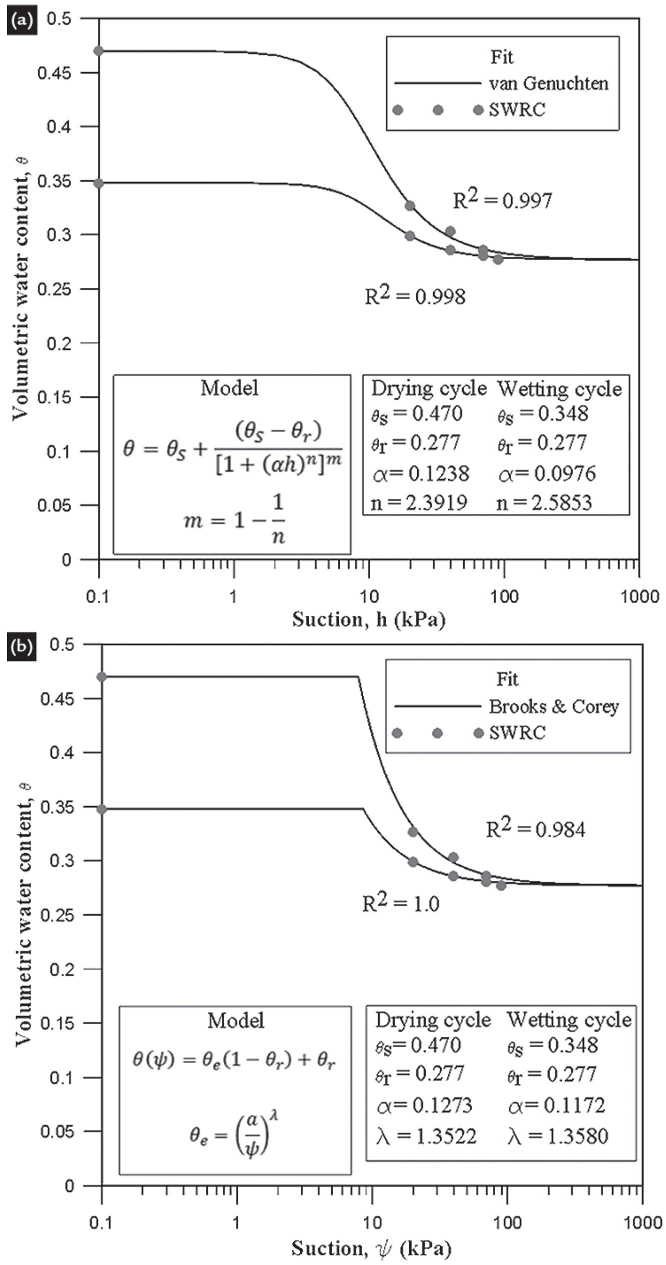

Figure 7
SWRC according to fitting models:
(a) van Genuchten;
(b) Brookes & Corey.

4. Conclusions

Test methods to obtain the soil water retention curve (SWRC) are still in development, as the existing ones require intensive labor or are very time consuming.

The technique that uses a flow pump system was implemented in the Mining Residue Laboratory at UFOP and applied to a silty sandy soil showing excellent results.

The overall assessment is that the new method is very convenient, fully automated, and produces reliable results in a fast and easy way, making this technique very promising.

5. Acknowledgements

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