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Laboratory Verification of a Proposed New Method to Determine the In-Situ Effective Porosity of Unsaturated Soil

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A laboratory validation of a proposed new method of determining the in-situ effective porosity of unsaturated soils was carried out on unsaturated river sand. The proposed method consists of boring a small diameter hole into the soil and inserting an Amplitude Domain Reflectometry (ADR) probe at the bottom part of the hole. Water is supplied into the hole till saturation and later de-saturated. The water content with time is determined from the ADR probe voltage potential readings. The effective porosity is determined from the difference between the saturated and de-saturated water contents. However, in the laboratory, the water is supplied through the top and bottom parts of the sample.

From the experiment the obtained effective porosity ranged from 0.28 to 0.29 for wetting from the top with an average of 0.287 and 0.29 to 0.30 for wetting from the bottom with an average of 0.293. The determined effective porosity ranged from 71.7-73.3 % of the real initial porosity of 0.40 of the river sand. The maximum attained degree of saturation during the experiment was 91%. The results indicated that the method will be suitable and useful in determining the effective porosity of medium grained unsaturated soils.

***Key words**: Underground dam, Effective porosity, Storage capacity, Freshwater development*

1 INTRODUCTION

One way to augment fresh water supply is to store run off in underground dams. Water in underground dams is relatively protected from evaporation, bacteriological contamination, does not breed mosquitoes to cause malaria, does not consume land and space and is cheaper to construct (Nishigaki, et al., 2004, Telmer and Best, 2004, Kankam-Yeboah, 2005). The challenges of estimating how much water an underground dam can store continuously face the technology. One main reason is that, the storage space is within the unsaturated soil whose properties such as hydraulic conductivity and effective porosity are difficult to determine in-situ. Osuaga (1997), Printz and Singh (2000), mentioned that for an underground dam of good storage capacity to be constructed, an aquifer with high effective porosity, sufficient thickness and great aerial extent should exist.

It has always been difficult to correctly estimate the storage capacity before construction. This arises from the fact that the right effective porosities of the soil layers are not usually known resulting in less storage or over estimated storage. In many cases, the effective porosity is determined empirically from particle size analysis curves.

In unconfined (water table) aquifers, the effective porosity equals the specific yield (Heath, 1983) which is determined from pumping test. Some engineers have therefore relied on the specific yield determined from Pumping test for the design. However, this method has limitations when dealing with the unsaturated soil or rock. Using effective porosity from the pumping test does not reflect the individual layers in the ground although multiple layer pumping tests have been used in some parts of the world. The specific yield determined is for a large area and does not reflect on the various layers within the aquifer. It is also impossible to apply this method to determine the effective porosity in unsaturated soils or rocks since no pumping can take place. An attempt to solve this problem has resulted in the proposal of a new technique to determine the effective porosity of the in-situ unsaturated zones (Akudago et al., 2005). The method, which makes use of the soil's dielectric properties, can be carried out using the domain reflectometry methods such as the Amplitude Domain Reflectometry (ADR).

The validity of the method was tested in the laboratory by determining the effective porosity of river sand using the Amplitude Domain Reflectometry (ADR) method. This paper presents the methodology, data and the

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determined effective porosity as well as the influencing factors of the ADR experiments which should be considered for the field measurements.

2 THE PROPOSED NEW METHOD FOR MEASURING IN SITU EFFECTIVE POROSITY

The proposed in situ method is very simple and cheap to carry out on the field. A hole of small diameter of about 6 to 8 cm is bored into the soil. An ADR probe connected to a data logger is inserted into the hole. Water is continually supplied into the hole until the zone close to the probe sensors is saturated. The water supply is then cut off and the water allowed to drain to the original residual equilibrium moisture content. The probe readings for both saturation and drainage processes are downloaded from the data logger into a computer. A graph of water content versus time is drawn and the effective porosity determined. The field setup is shown in **Fig.1** whilst **Fig.2** shows the typical water content against time graph on the field. Prior to carrying out the in-situ test, the in-situ soil sample should be taken for a calibration test in the laboratory. This calibration gives a relation between water content and the probe readings.

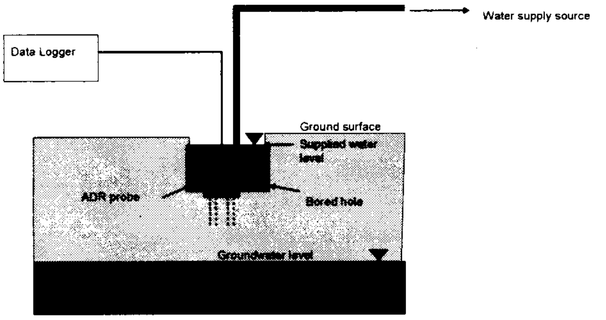

Fig.1 Field setup to determine the in-situ effective porosity

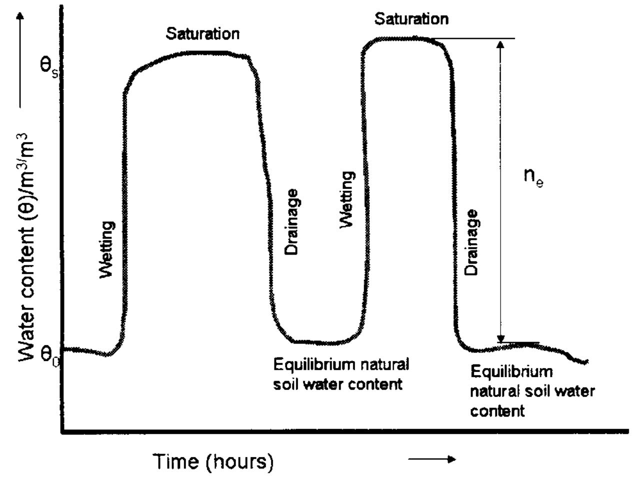

Fig.2 A typical water content versus time curve on the field

However, Topp et al. (1980) obtained the relationship between the volumetric water content, dielectric constant and the probe output for various soils and could be used. However, the use of the general calibration curve could introduce a slight error in the water content values.

3 LABORATORY EXPERIMENT

3.1 Laboratory Apparatus and Instrumentation

The apparatus comprises 10 and 50 cm diameters, 1m high cylinders closed at the bottom with valves, water supply tank, electronic balance, connecting hose and the ADR Probe connected to a data logger. Figures 3a and b respectively show the experimental set up in the laboratory using the 10 and 50 cm diameter cylinders.

3.2 Sample Preparation and Experimentation

River sand of 2.67g/cm^3 and initial porosity of 0.4 was compacted into an 80cm column of diameter 10 cm. The first 5 cm (bottom portion) was filled with gravel of 2-5mm diameter size to prevent clogging around the bottom valve as shown in **Fig.3a**.
Above and below the gravel pack were thin stainless steel gauze filter to further reduce the risk of blocking the valve. The sample was saturated from the bottom with non- dissolved air (de-gassed) water after carbon dioxide gas was passed into the sample to expel trapped air. The sample was de-saturated till a water level of 10 cm from the bottom was attained as shown in **Figs.3**. After this initial saturation-de-saturation process in order to homogenize the sample, it was later re-saturated from the top while maintaining the 10 cm water level fixed and both valves opened. The process was repeated and later with water supply gradually (5 cm interval) from bottom till saturation. The process was repeated a number of times. The change (rise and fall) in water content of the sample during the saturation and de-saturation was determined by a permanently (from beginning to end of experiment) inserted vertical ADR probe at the 80 cm level in volts. The readings were then converted to water contents by calibrating the soil and finding a relation between the water content and the probe readings as in equation (1). The experiment was repeated for the river sand using a bigger device of 50 cm diameter (**Fig.3b**). Figure 4 shows the particle size distribution curve of the river sand. The continuously drained water was measured on the electronic balance which helped in determining the period of completed drainage.

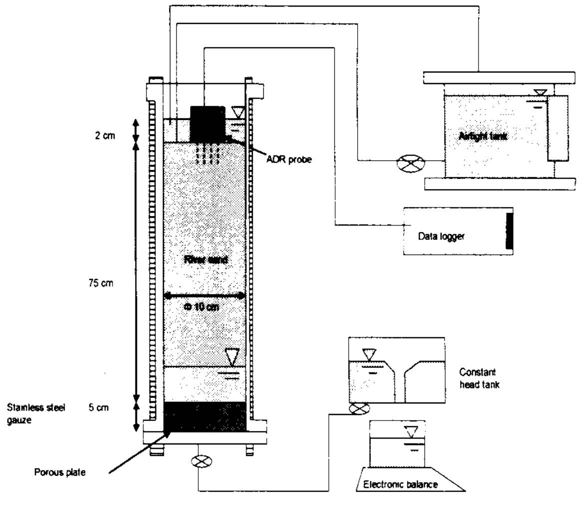

Fig.3a Laboratory experimental setup showing only a vertical ADR probe

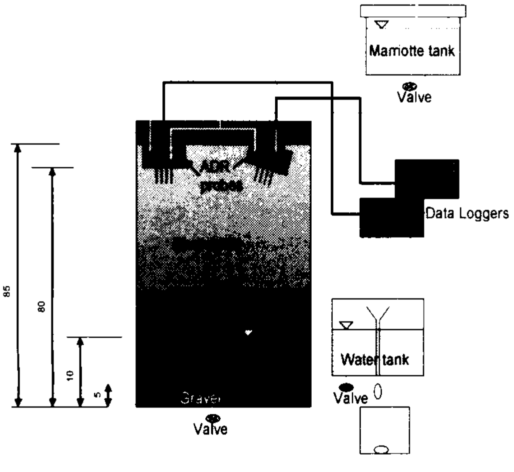

Fig.3b Laboratory experimental setup showing both ADR probes in the 50 cm diameter column

4 RESULTS AND DISCUSSION

For the purpose of converting the probe output (volt) to volumetric water content, the calibration equation of Nishigaki et al. (1998) was used.

$$\theta = 0.425v^5 - 0.799v^4 + 0.956v^3 - 0.740v^2 + 0.749v - 0.083 \quad (1)$$

where, θ is the water content of the soil and v is the probe output in volts.

The data acquired from the experiments were plotted on graphs as shown in **Fig.5** to **Fig.7**.

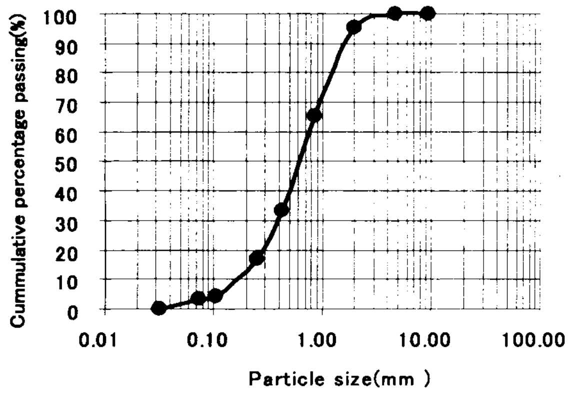

Fig.4 Particle size distribution curve of river sand

The graphs are sinusoidal in shape and similar to the one in **Fig.2** with the crest indicating saturation whilst the troughs indicate de-saturation. The determination of the effective porosity is based on the fact that in unconfined aquifers, the volume of water stored or released equals the specific yield. In the case of the 10 cm diameter container, the difference in water contents between the saturated point and a day's drainage was taken as the effective porosity. However, in the 50 cm diameter experiment, the drainage time was increased to at least four (4) days. This was decided based on the fact that it takes at least a day to pump a well on the field to attain steady state condition (Kasenow, 2001). Also, for sand aquifers, a minimum of 30 hour pumping is required for the aquifer parameters to be estimated (US Geological Circular USGS, 1998). Considering the fact that the particle sizes are small, the flow in an unsaturated condition will be longer due to the larger number of small pores (Kays et al., 2005), hence, 24 hours after drainage had begun, was thought to be enough time for the effective porosity n_e to be estimated. More so, since the drainage valves in both containers are the same in dimension, the time for steady state was increased to at least four days in the 50 cm diameter column to cater for the large area of drainage. The summary of the results of the effective porosities are shown in Table 1.

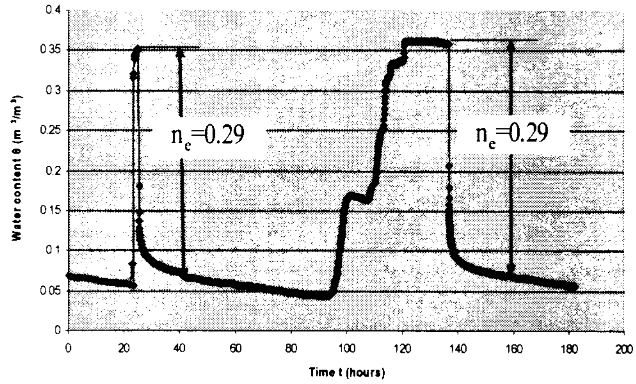

Fig.5 Water content versus time for river sand (vertical ADR probe in small column)

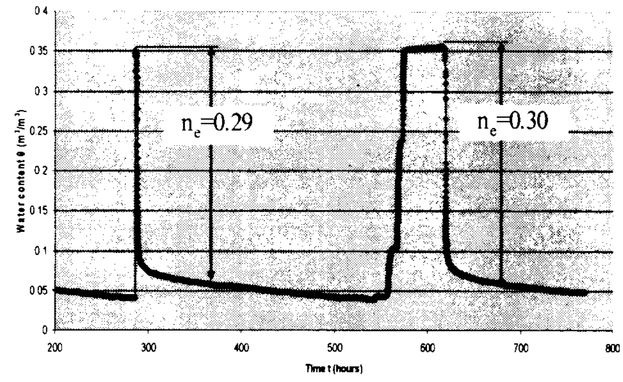

Fig.6 Water content versus time for river sand (inclined ADR probe in bigger column)

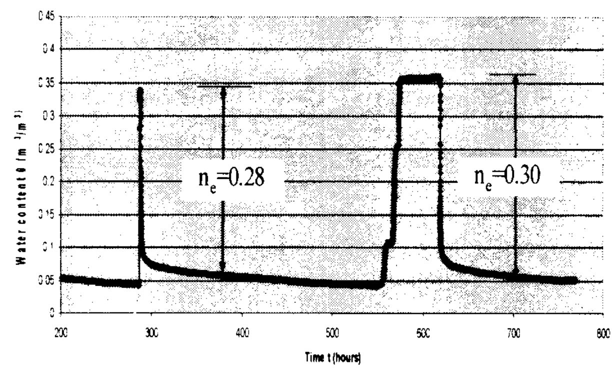

Fig.7 Water content versus time for river sand (vertical ADR probe in bigger diameter column)

The value of the effective porosity when water was supplied from the top is considered as the experimental effective porosity whereas that of the bottom supplied water source is the real or actual effective porosity of the soil. Generally, and for design purposes, experimental value should be less than or equal to the real value. If the experimental value is less than the real value, then a higher storage can result where as the reverse results in lower volume. Considering the laboratory experiments, there was no so much difference in the values of the effective porosity from the two water supply directions. The values ranged from 0.28 to 0.29 and 0.29 to 0.30 respectively for water supply from top and bottom. However, the values of saturations differed slightly in some cases by at most ± 0.01. The de-saturated water content was almost the same in all the experiments except supplying the water from the top where the difference is at most ± 0.02. According to the Institute of Food and Agricultural Sciences of University of Florida (UF/IFAS), measurements taken by ADR probe are affected by air gaps, stones or channeling water directly onto the probe rods. Again, the probe sensors are sensitive within a region of about 3cm radius with an accuracy range of ±0.01-0.05 m^3m^{-3}, hence, the water contents at saturation fall within the instrument error limits. The maximum degree of saturation was about 91%.

Table1 Summary of river sand ADR experimental results

Water supply direction	Water content at saturation	Water content at de-saturation	Effective porosity (n_e)
Top to bottom			
ADR1 river sand (RS)	0.35	0.06	0.29
ADR 4 RS (inclined)	0.35	0.06	0.29
ADR 5 RS (vertical)	0.34	0.06	0.28
Average			0.287
Bottom to top			
ADR1 RS	0.36	0.07	0.29
ADR4 RS (Inclined)	0.35	0.05	0.30
ADR5 RS (vertical)	0.35	0.05	0.30
Average			0.293

On the practical field, the water can not be raised from the bottom to determine the effective porosity as was done in the laboratory and so a laboratory relationship between the effective porosities from both directions is of paramount importance.

When water is being raised from the bottom upwards, there are two forces that cause the flow: Capillary forces and the pressure head difference. The capillary forces prepare the region against the occupation of air particles in the voids by pre-wetting the capillary area. The pressure head then causes more saturation when the water table in the soil sample is raised. On the other hand, when water is supplied from the top, the flow is driven by gravity and the saturation may be less than that from the bottom due to faster flow. If the velocity of the supplied water is more than the velocity of flowing water in the soil sample, there will be stagnation. This could increase the dielectric readings if spaces exist around the probe sensors. In the situation where there is no adequate compaction (loose compaction) and spaces exist around the ADR region or 3 cm from the probe sensors, there could be a rise in water content since the probe will be recording higher dielectric values due to pool of water surrounding the probe sensors. According to Delta-T Devices Ltd (1996), it is advisable to leave the ADR probe buried in an inclined position in order to allow free flow of water for better results. However, the experiment of the river sand using the 50 cm diameter cylinder had two ADR probes, one inclined and the other in a vertical position as in **Fig.3b**. The results obtained showed that there was no so much difference in the ADR readings from inclined and vertical positions. However, in supplying water from the top, the inclined ADR probe showed slightly higher readings at saturation.

5 Estimating the volume of the underground dam

The volume of the underground dam can be estimated from equation (2)

$$V = n_e AH \tag{2}$$

where,

n_e: the effective porosity of the unsaturated zone
A: the area of the unsaturated
H: the height of expected water rise from groundwater level

Applying a factor of safety α to the design, then the estimated designed volume becomes equation (3)

$$V = (1-\alpha) n_e AH \tag{3}$$

where, α is far less than 1.

6 CONCLUSION AND RECOMMENDATIONS

A laboratory experiment was conducted on river sand to determine the unsaturated effective porosity using the ADR method. The aim was to use the experiment to validate a proposed in-situ method to determine the effective porosity of unsaturated soils for the purpose of estimating underground dams' volumes. The average effective porosity value was 0.287 for wetting from the top and 0.293 from bottom respectively. These values are respectively 71.8% and 73.3% respectively of the initial porosity. Both directions' effective porosities differ from each other by 1.5% and indicate that on the field, the water supply from the top is adequate to yield good results. The maximum attained degree of saturation during the experiment was 91%. The results showed that the proposed method would be useful in determining the in-situ effective porosities of medium grained unsaturated soils. Field experiments are yet to be carried out to validate the method and possible limitations.

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