

ALCOA OF AUSTRALIA

No. 33

**A PROCEDURE FOR INSTALLING NEUTRON
PROBE ACCESS TUBES INTO BAUXITE-
PROCESSING RESIDUE SAND PROFILES**

I. R. Phillips
August 2010

SUMMARY

A method for installing neutron probe access tubes into bauxite-processing residue sand (hereafter termed residue sand) profiles is described. This method relies on removing residue sand from within the access tube by applied suction as the tube is hammered into the profile. The method can install neutron probe access tubes to depths of at least 6 m, and performs best in loose, dry materials such as coarse-textured residue sand. The installation procedure ensures excellent contact between the outside perimeter of the tube and the surrounding residue sand. A Didcot moisture density gauge was calibrated using a range of volumetric water contents (θ_v) that were obtained by detailed sampling of residue sand profiles at two imposed moisture conditions (i.e. dry and wet). Linear regression of the neutron count ratio (CR) against θ_v produced an equation with a slope of 0.85, and a root mean square error (RMSE) of $0.011 \text{ m}^3/\text{m}^3$. The pH and salinity of residue sand did not significantly ($p < 0.05$) affect CR. Although CR tended to increase with increasing ρ_b , inclusion of this parameter with θ_v did not improve the correlation coefficient ($r^2 = 0.941$). Therefore, it was concluded that a regression equation relating CR to θ_v only was suitable for measuring the moisture content of residue sand.

INTRODUCTION

Refining bauxite ore to alumina, by digestion with hot concentrated sodium hydroxide, generates approximately 2 tonnes of residue (non-soluble ore components) per 3 tonnes of bauxite. In Western Australia, Alcoa of Australia (Alcoa) produces up to 60,000 tonnes of residue per day, but unlike other refineries, separates its residue into coarse ($>150 \mu\text{m}$) and fine ($<150 \mu\text{m}$) fractions. The coarse fraction (residue sand) is used to construct embankments, which form storage areas to contain the fine fraction (residue mud).

Alcoa is currently evaluating the role of store-and-release covers as a long term management strategy for minimising drainage from operating and closed residue storage areas. Recent studies have found that residue sand typically exhibit plant available water and saturated hydraulic conductivity values of approximately $0.2 \text{ m}^3 \text{ m}^{-3}$ and 20 m d^{-1} , respectively (Banning *et al.* 2010). Consequently, residue sand embankments exhibit extremely poor water holding properties, thereby allowing a high proportion of infiltrating water to percolate through the profile to become deep drainage. Quantifying drainage volumes *in-situ* at the field scale is extremely difficult, and this parameter is often estimated using the water balance

approach. This approach, however, relies on accurate measurements of precipitation, infiltration, evapotranspiration and changes in soil water storage.

The soil volumetric water content (θ_v) at a specific depth can be measured directly, or estimated using indirect methods. The direct (gravimetric) method is a simple and robust method of proven accuracy (Topp and Ferre 2002). As such, the accuracy of the gravimetric method allows it to be used for calibration of all other techniques. However, the method is destructive, difficult to obtain samples at depths >1 m, labour-intensive, and inappropriate for use where long term sampling can compromise the hydraulic properties of experimental sites. When using indirect methods, θ_v is derived by inference through the use of well-established relationships that link soil water content to a measured soil parameter. The two most common indirect methods in soil water movement studies are the use of neutron scattering and dielectric sensors. Of these two methods, neutron scattering has consistently been found to be the most efficient and accurate method of measuring moisture content profiles in the field (Evetts and Steiner 1995; Hignett and Evett, 2002; Mwale *et al.* 2005).

Residue sand is extremely alkaline (pH >10) and extremely saline (electrical conductivity >3 dS m^{-1}) (Phillips and Chen 2010). As such, residue sand is a highly corrosive medium which can severely limit the working life of many field instruments and equipment installed *in-situ*. Furthermore, residue sand profiles are largely devoid of structural stability (particularly for $\theta_v < 0.05$ $m^3 m^{-3}$) which makes coring and maintaining hole stability extremely problematic. Consequently, developing a vertical cavity in a residue sand profile to allow installation of an access tube is very difficult, particularly if the tube is to be installed to depths >2 m.

Aluminium access tubes are commonly used in conjunction with neutron scattering techniques because this material has minimal effect on neutrons. However, aluminium tubes are relatively expensive, not particularly strong, and can quickly corrode in saline and alkaline conditions (Hignett and Evett 2002). Therefore, aluminium tubes would not be suitable for long term use in residue sand, and other materials more suitable to the aggressive conditions of residue sand are required. Such materials include polyethylene, polyvinyl chloride (PVC), mild steel, and stainless steel. All of these materials have advantages and disadvantages in terms of cost, availability, suitability for use in specific soil types (acid, alkaline, saline, stoney, clay soils); however, a major consideration is the ability of the materials to affect neutron count values (Hignett and Evett 2002).

Polyethylene tubing can increase the neutron count values by up to 20% relative to aluminium tubing due to the hydrogen and carbon contained in this material. Polyvinyl chloride (PVC) tubing can reduce the count value by up to 50% relative to aluminium tubing because of neutron capture (absorption) by the chloride atoms in PVC (Allen and Segura 1990; Allen *et al.* 1993). Mild steel tubing is cheap, strong, and will last for at least 3 years in all but very acid soils, but has the disadvantage that it absorbs neutrons and decreases sensitivity of the moisture gauge by about 2%. Although stainless steel also suffers from a loss of sensitivity relative to aluminium, this material appears to be most suitable for use in residue sand due to its inherent strength and durability in a hostile chemical and physical environment. Importantly, however, the accuracy of the water content determined by the neutron scattering technique is much more dependent on other factors (such as tube installation, unaccounted for soil properties and calibration) than on the material used for access tubing (Ruprecht and Schofield 1990; Hignett and Evett 2002).

The primary aim of this study was to describe a simple procedure for deep installation of neutron probe access tubes in loose, dry residue sand profiles.

MATERIALS AND METHODS

Site Selection

Neutron probe access tubes were installed at Alcoa's Pinjarra Refinery in Western Australia (S32 38.143 E115 54.789) on a 3 year old, unvegetated residue sand embankment. This embankment had previously only received 200 t ha⁻¹ of gypsum to reduce sodicity and alkalinity.

Installation Procedure

Four stainless steel tubes (44 mm o.d. by 1.6 mm wall thickness) were installed to a depth of about 3 m as described below. The outlined procedure has however been used to successfully install tubes to a depth of up to 6 m in residue sand profiles. A tube diameter of 44 mm was selected to maximize probe sensitivity during neutron counting, and to provide sufficient tolerance to ensure the probe could move freely, even if there were small distortions in the tube (Hignett and Evett 2002).

The installation process essentially involved extracting the residue sand from within the steel tube as it was hammered into the profile. The sand was extracted using a standard industrial vacuum cleaner, with the vacuum hose attached to a 3.5 m steel tube (25 mm o.d. by 1.0 mm wall thickness, hereafter referred to as the extraction tube). It was critical that the bend in the extraction tube was great enough ($> 45^\circ$) to allow the extracted sand to flow freely without clogging. The essential items of equipment for installing the neutron probe access tube are provided in Figure 1, and include (1) the stainless steel tube, (2) an anvil and slide hammer, (3) a base plate for locating the tube, (4) a sand extraction tube, and (5) an industrial vacuum cleaner and vacuum hose.

Prior to commencing installation, the stainless steel tube was cut to a length equal to the depth to which the tube was to be installed, plus an additional 100 mm above ground for the neutron moisture meter to sit during moisture measurements. The anvil (collar) was then attached to, and the slide-hammer passed over, the stainless steel tube, with the top of the anvil set at a maximum height of about 1200 mm above ground level to minimise over-extension when raising the hammer. The sand extraction tube was placed inside the (44 mm) access tube, and securely attached to the vacuum hose. The base of the tube was located into the base plate, and the entire assembly orientated to the vertical position. A “bubble level” was used to ensure the access tube remained as vertical as possible during installation. If not vertical, then subsequent problems with use of the neutron moisture probe will be encountered (i.e. the probe will not slide freely to depth within the access tube). It was important to set the height of the sand extraction tube to ensure its base extends about 20 mm below the access tube. This allowed the sand at the leading edge of the access tube to be removed, thereby reducing friction as the tube was hammered into the ground.

Vacuuming commenced once the assembly became stable. In loose, dry sand, the access tube generally moved rapidly into the sand profile with minimum requirement for additional hammering, and the access tube became quite stable in a very short time period. However, when it was necessary to utilise the hammer and anvil, it is recommended that the hammer be raised no higher than eye-level (or 1200 mm above ground level at a maximum) and released. The action of the hammer contacting the anvil pushed the tube into the residue sand profile. It was found that the access tube should be installed in small increments (about 20 mm) to avoid removal of excess quantities of sand and risk potential clogging of the vacuum hoses. It was also found that by continuously moving the sand extraction tube in an up-and-down

motion (approximately 100 mm), it would loosen the sand surface immediately below the installation tube, which was then sucked up and blown into the vacuum cleaner. When the base of the anvil reached ground level, it was re-positioned to a height of about 1200 mm above ground level and hammering re-commenced. This process was repeated until the stainless steel tube had been installed to the desired depth, and 100 mm of tube extended above ground level for subsequent support of the neutron moisture meter. The base of the access tube was sealed against water ingress by a PVC bung.

Neutron Probe Calibration Procedure

The neutron probe used in this study was a Didcot Soil Moisture Gauge (Didcot Instruments, Wallingford, UK), and was calibrated against volumetric water content (θ_v) determinations in residue sand over a wide range of moisture content. Two of the installed tubes were used to calibrate the neutron probe at a range of dry conditions (i.e. low θ_v) and the remaining two to obtain a range of wet conditions (i.e. high θ_v). This was achieved by performing the tests when the residue sand profile was as dry as possible (i.e. during late-summer), and within 24 hours after a large rainfall event (i.e. late-winter when the water content of the residue sand profile was greatest). The two pairs of tubes were installed approximately 20 m away from each other to provide an adequate buffer zone.

Immediately prior to sampling, readings using the Didcot Soil Moisture Gauge were taken in each access tube at 0.2 m intervals to the depth of the tube (approximately 3 m). Immediately following these readings, the top of the residue sand profile was marked on the tube, and an excavator used to dig a 1 m deep trench within 0.5 m from the access tubes. Marking the position of the surface ensured accurate depth measurements could be recorded as the material surrounding the tube was subsequently removed. Two undisturbed cores (PVC tubes 100 mm long by 50 mm i.d.) of residue sand were collected every 0.2 m to ensure that the initial readings by the Didcot Moisture Gauge were directly related to the moisture content at each measured depth. After removal from the residue sand profile, the PVC tube was immediately wrapped in plastic wrap to protect the residue sand core from moisture and material loss during transport to the laboratory.

The residue sand samples were retained for bulk density (ρ_b), porosity and θ_v determination using standard procedures (Duane and Topp 2002). Grab samples were also collected every

0.2 m for pH and electrical conductivity (EC) determination using a sand to water ratio of 1:5 (Rayment and Higginson 1992).

Statistical Analysis

Comparison of mean values for residue sand pH, EC, porosity and θ_v were analysed using analysis of variance (ANOVA) and least significant differences (LSD, $P < 0.05$) procedures (Analytical Software 1994). All curve fitting was done using the software package Grapher 3 (Golden Software 2000).

RESULTS AND DISCUSSION

General Properties of Residue Sand Profile

The pH increased steadily from about 8 in the surface to >11 at 1.2 m, after which the pH remained relatively constant (Figure 2). Below a depth of 1.2 m, pH values were not significantly ($p < 0.05$) different from each other. Furthermore, the mean pH of the profile did not differ significantly between sampling times (dry or wet conditions) and replication. Although similar patterns were observed for EC, this parameter increased steadily to a depth of 1.8 m, below which the EC remained relatively constant ($p < 0.05$). The study site had received about 200 t ha^{-1} of gypsum incorporated over a depth of about 1 m, and two years of rainfall, prior to neutron probe access tube installation. Gypsum and rainfall can reduce the pH and EC of residue sand via precipitation of CaCO_3 and leaching of soluble salts, respectively, and these two processes are known to play an important role in defining the chemical characteristics of residue sand profiles (Banning *et al.* 2010; Phillips and Chen 2010).

In contrast, bulk density (ρ_b) steadily increased with depth, ranging from 1.3 Mg/m^3 in the 0.2 – 0.4 m interval to 1.5 Mg m^{-3} below a depth of 2 m (Figure 3). The lowest values of ρ_b were found in the 0 – 0.8 m interval, which was consistent with the depth of mechanical disturbance of the profile due to gypsum incorporation.

The average water content (θ_v) of the 0 – 3 m profile was significantly ($p < 0.05$) different between the two sampling times (dry = $0.128 \text{ m}^3 \text{ m}^{-3}$ versus wet = $0.209 \text{ m}^3 \text{ m}^{-3}$). This satisfied the requirement of obtaining neutron probe data for two contrasting moisture conditions. However, at no stage did θ_v equal total porosity (Figure 3). This finding was not

unexpected as saturated conditions are very rarely experienced in residue sand profiles due to their highly permeable character (i.e. $k_{\text{sat}} > 20 \text{ m d}^{-1}$).

Effect of Residue Sand Properties on Didcot Moisture Gauge Count Ratio (CR)

There was no significant ($p < 0.05$) relationship between CR and EC, and CR and pH (Figure 4). Of the measured parameters, CR was most strongly correlated with θ_v ($r^2 = 0.94$) and to a lesser extent, ρ_b ($r^2 = 0.37$). Including other parameters such as pH and EC did not improve the correlation relative to θ_v alone. It was expected that gypsum may have affected the CR as noted by Evett *et al.* (2007). The absence of any significant effect of pH and EC on CR suggests that gypsum was not present in concentrations sufficiently high enough to increase thermalization of neutrons, thereby increasing CR. Although there was a trend for increasing CR with increasing ρ_b , multi-linear regression analysis using θ_v and ρ_b did not improve the correlation coefficient relative to using θ_v alone. Thus, there was no reason to invoke separate regression equations for the gypsum- and non-gypsum- amended depth intervals of the residue sand profile, and that the influence of ρ_b on CR in the residue sand embankments could effectively be ignored.

Calibration Equation and Comparison to Published Studies

The linear regression equation for describing θ_v of residue sand using a Didcot Moisture Gauge had a slope of 0.85, an r^2 of 0.94, and a root mean square error (RMSE) of $0.011 \text{ m}^3 \text{ m}^{-3}$. The mean measured θ_v across all 44 residue sand samples was $0.16 \text{ m}^3 \text{ m}^{-3}$, with lower and upper 95% confidence intervals of 0.145 and $0.175 \text{ m}^3 \text{ m}^{-3}$ respectively. In comparison, the mean predicted θ_v across all 44 residue sand samples was $0.16 \text{ m}^3 \text{ m}^{-3}$, with lower and upper 95% confidence intervals of 0.146 and $0.172 \text{ m}^3 \text{ m}^{-3}$ respectively. These results demonstrated a very good agreement between measured θ_v by the traditional gravimetric procedure and θ_v predicted using the Didcot Moisture Gauge.

Reported calibration equations for neutron moisture probes, and specifically the Didcot Moisture Gauge, for use in bauxite-processing residue sand could not be sourced in the published literature. Therefore, direct comparison of the regression equation presented in this study to other studies was not possible. However, various studies have been reported in the literature on the use of this gauge in the lateritic soils of the Del Park catchment of the Darling Ranges, Western Australia. Ruprecht and Schofield (1990) experienced major

difficulties in providing a calibration equation for these soils due to their highly variable textural properties and issues with access tube installation. Croton and Raper (1996) re-analysed the data by Ruprecht and Schofield (1990) and whilst no improvement in the data analysis could be made, selectively culling data provided a calibration curve with a slope of 0.58, an intercept of -0.05 and an r^2 of 0.74.

A comparison of the calibration equation presented here with those derived for soils in the south-west of Western Australia are provided in Table 1, together with the recommended equations by the Institute of Hydrology, United Kingdom (Ruprecht and Schofield 1990). Clearly, there is significant variability between these equations, except for the equation recommended by the Institute of Hydrology. Interestingly, a study by George (1999) using a CPN 503DR Hydroprobe containing an Am-241/Be (1.85 GBq, 50 mCi) source (same as the Didcot Moisture gauge), reported a calibration curve for a Brown Chromosol soil at Dubbo, NSW, Australia, as: $\theta_v = 0.854CR - 0.084$, which is similar to the equation derived in this study.

Using the Calibration Equation For Measuring θ_v in Residue Sand Profiles

Examples of the distribution of θ_v to a depth of nearly 3 m following rainfall (wetting) and drying events in 2008 are presented in Figure 5. Between the 4th March and 1st April, the site received 51 mm of rainfall, increasing θ_v in the 0 – 0.2 m interval from 0.02 to 0.17 m³ m⁻³ (Figure 5a). There were no measurable changes in θ_v below a depth of 0.6 m, and > 90% of the infiltrating water was found to be retained in the 0 – 0.6 m depth interval. Between 1st April and 2nd June, the site received an additional 290 mm of rainfall, which increased θ_v throughout the 0 – 2 m depth interval (Figure 5a). The Didcot Moisture Gauge estimated that again > 90% of the infiltrated water resided within the 0 – 2 m depth interval, and this percentage was validated (data not presented) using the one dimensional water transport model HYDRUS (Simunek and van Genuchten 1999).

In the absence of water inputs (i.e. rainfall), the residue sand θ_v profile gradually dries out (Figure 5b). The extent of drying was most pronounced in the 0 – 1 m depth interval, with smaller changes at greater depths. Although drainage under unsaturated flow conditions continued to occur throughout the drying period, bare soil evaporation also contributed to greater water loss in the upper profile (data not presented).

CONCLUSIONS

A method of installing neutron probe access tubes in loose, sandy material to depths of at 6 m is described. The method uses readily available equipment and can be installed by a minimum of two people. The method ensures excellent contact between the outside surface area of the access tube and the surrounding soil, which is critical to obtaining reliable neutron count data. The procedure can be readily modified for installing other field equipment into the unsaturated soil zone such as tensiometers.

A Didcot Soil Moisture Gauge was calibrated over a range of water contents and the resulting linear regression equation was found to provide very good estimates of residue sand water contents over a range of wetting and drying events.

ACKNOWLEDGEMENT

Alcoa acknowledges the expertise provided by Mr James Croton of Water & Environmental Consultants (WEC) in designing and providing assistance in the construction and operation of the access tube installation equipment.

REFERENCES

- Allen RG, Segura D (1990) Access tube characteristics and neutron meter calibration. In "Irrigation and drainage". (Ed SR Harris) pp. 11–13 (Proceedings of 1990 National Conference, Durango, Colorado, New York, New York: American Society of Civil Engineering)
- Allen RG, Dickey G, Wright JL (1993) Effect of moisture and bulk density sampling on neutron moisture gauge calibration. In "Management of irrigation and drainage systems, Integrated perspective" (Eds RG Allen, CMU Neale) pp. 1145–1152 (Proceedings of 1993 ASCE National Conference on Irrigation and Drainage Engineering, Park City, Utah, July, New York, New York: American Society of Civil Engineering)
- Analytical Software (1994) "Statistix". (Analytical Software: Florida, USA)
- Banning NC, Phillips IR, Jones DL, Murphy DV (2010) Development of microbial diversity and functional potential in bauxite residue sand under rehabilitation. *Restoration Ecology* doi: 10.1111/j.1526-100X.2009.00637.x

- Croton JT, Raper GP (1996) Calibration of the neutron soil moisture meter at the Del Park catchment. Unpublished report by Water & Environmental Consultants, Report to the Water & Rivers Commission, July, Western Australia, Australia
- Duane JH, Topp GC (2002) “Methods of soil analysis, part 4: Physical methods”. (Soil Science Society of America: Madison, Wisconsin)
- Evett SR, Steiner JL (1995) Precision of neutron scattering and capacitance type soil water content gauges from field calibration. *Soil Science Society of America Journal* **59**, 961–968
- Evett S, Ibragimov N, Kamilov B, Esanbekov Y, Sarimsakov M, Shadmanov J, Mirhashimov R, Musaev R, Radjabov T, Muhammadiyev B (2007) Neutron moisture meter calibration in six soils of Uzbekistan affected by carbonate accumulation. *Vadose Zone Journal* **6**, 406–412
- George BH (1999) Comparison of techniques for measuring the water content of soil and other porous media. (Masters Thesis, Department of Agricultural Chemistry & Soil Science: University of Sydney, NSW, Australia)
- Golden Software (2000) “Grapher™ User’s Guide. Graphing software for scientists and engineers”. (Golden Software: Colorado, USA)
- Hignett C, Evett SR (2002) Neutron thermalisation. In “Methods of soil analysis, part 4: Physical methods”, (Eds JH Duane, GC Topp) pp. 501–521, (Soil Science Society of America: Madison, Wisconsin)
- Mwale SS, Azam-Ali SN, Sparkes DL (2005) Can the PRI capacitance probe replace the neutron probe for routine soil-water measurement? *Soil Use and Land Management* **21**, 340–347
- Phillips IR, Chen C (2010) Surface charge characteristics and sorption properties of bauxite-processing residue sand. *Australian Journal of Soil Research* **48**, 77-87
- Rayment GE, Higginson FR (1992) “Australian laboratory handbook of soil and water chemical methods” (Inkata Press: Melbourne, Australia)
- Ruprecht JK, Schofield NJ (1990) In-situ neutron moisture meter calibration in lateritic soils. *Australian Journal of Soil Research* **28**, 153-165
- Simunek J, van Genuchten M Th (1999) Using the HYDRUS-1D and HYDRUS-2D codes for estimating unsaturated soil hydraulic and solute transport parameters. In “Characterization and measurement of the hydraulic properties of unsaturated porous media”, (Eds M Th van Genuchten, FJ Leij, L Wu), pp. 1523-1536. (Riverside, California: University of California)

Topp GC, Ferre PA (2002) Methods for measurement of soil water content. In “Methods of soil analysis, part 4: Physical methods”, (Eds JH Duane, GC Topp), pp. 422–424, (Soil Science Society of America: Madison, Wisconsin)



Figure 1. Essential equipment required for installing neutron probe access tubes in residue sand profiles. (1) the stainless steel tube, (2) an anvil and slide hammer, (3) a base plate for locating the tube, (4) a sand extraction tube, and (5) an industrial vacuum cleaner and vacuum hose.

(a) Progressive excavation for sampling of residue sand



(b) Close up of sample collection



Figure 2. Progressive collection of residue sand samples for moisture, bulk density, pH and EC analysis.

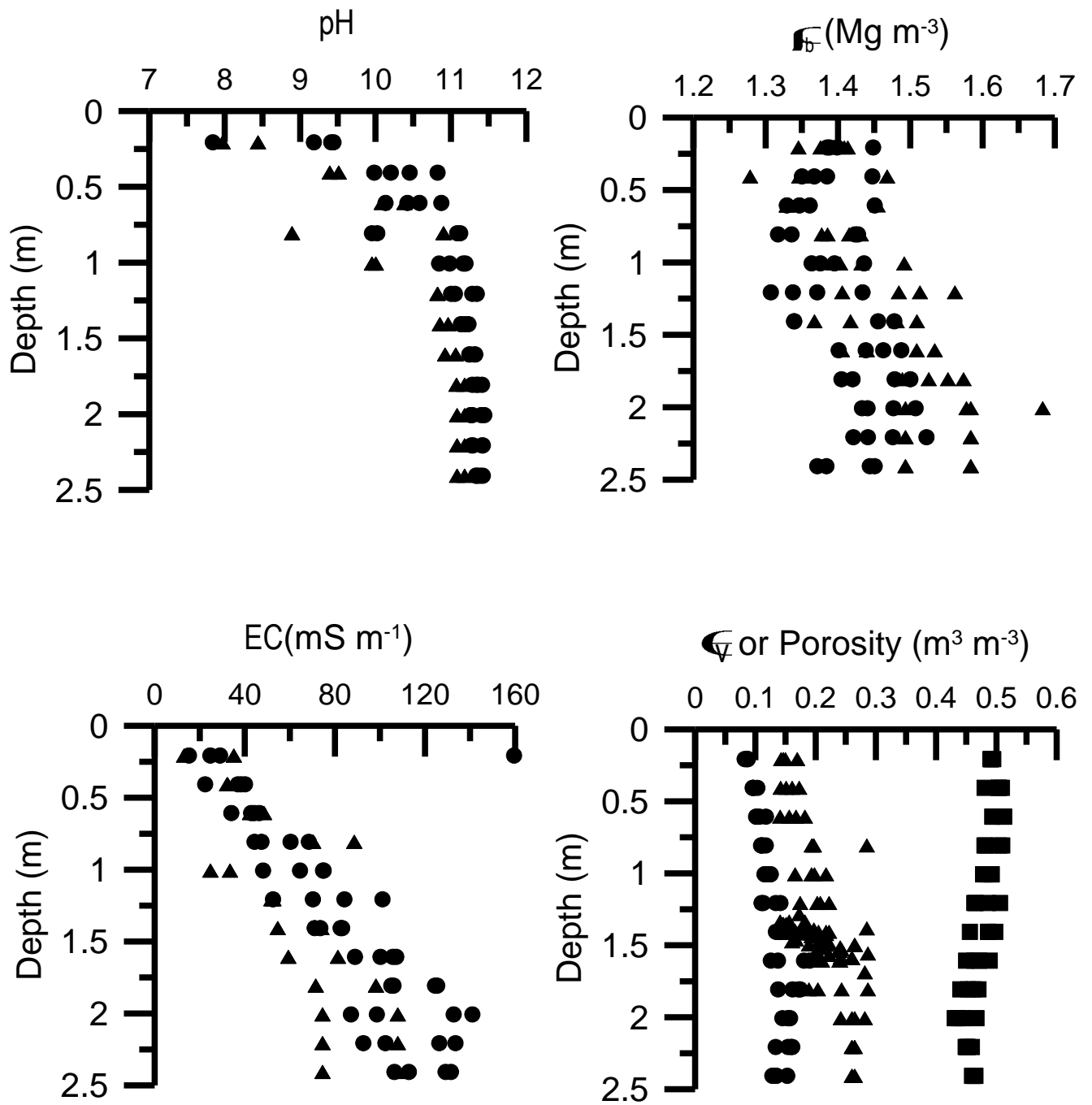


Figure 3. Distribution of pH, ρ_b , EC, porosity and θ_v as a function of depth (n = 96). ● = data from dry conditions, ▲ = data from wet conditions, ■ = porosity data for all samples

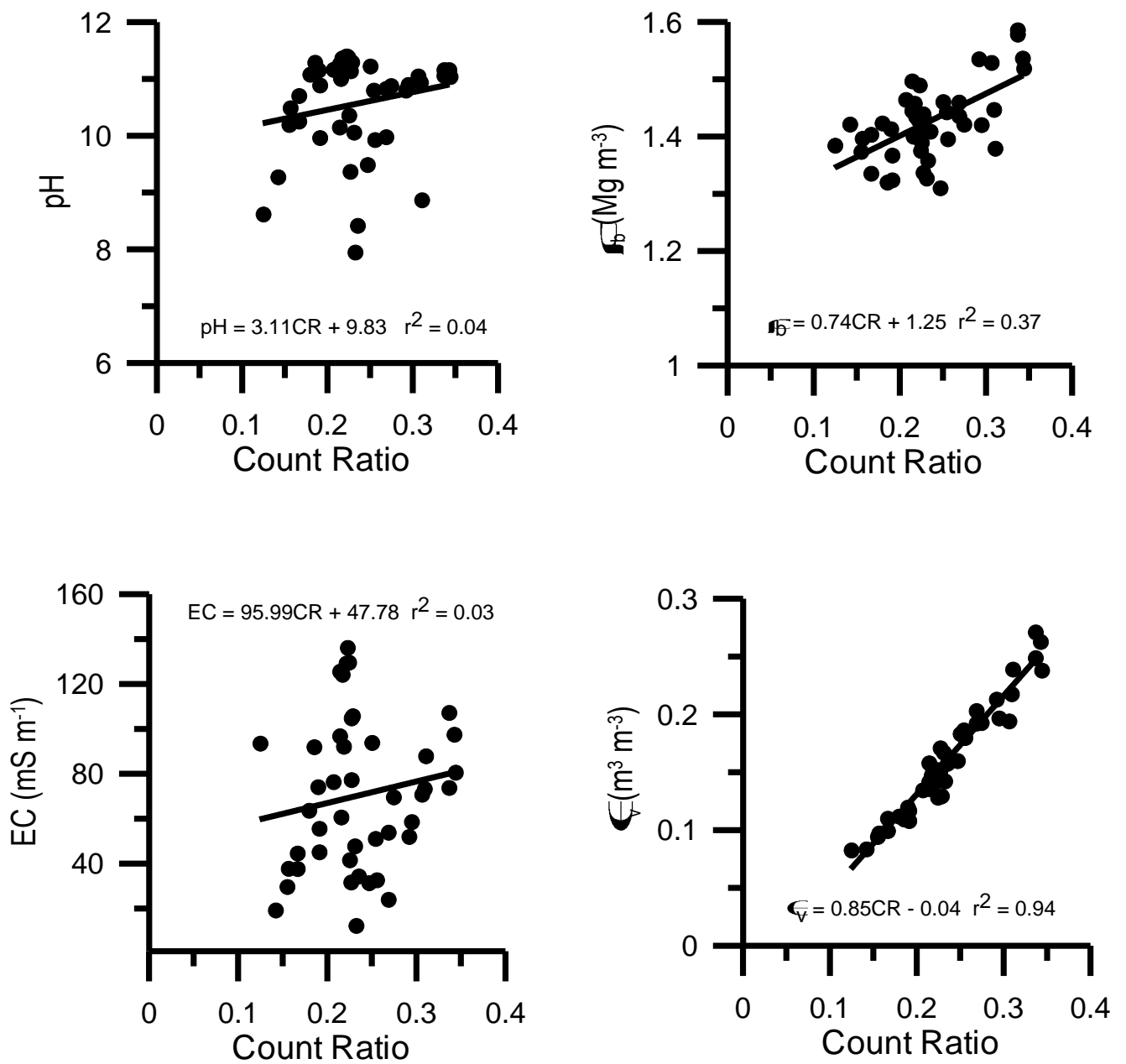


Figure 4. Relationship between CR with pH, ρ_b , EC and θ_v . • = measured data, solid line = linear regression line

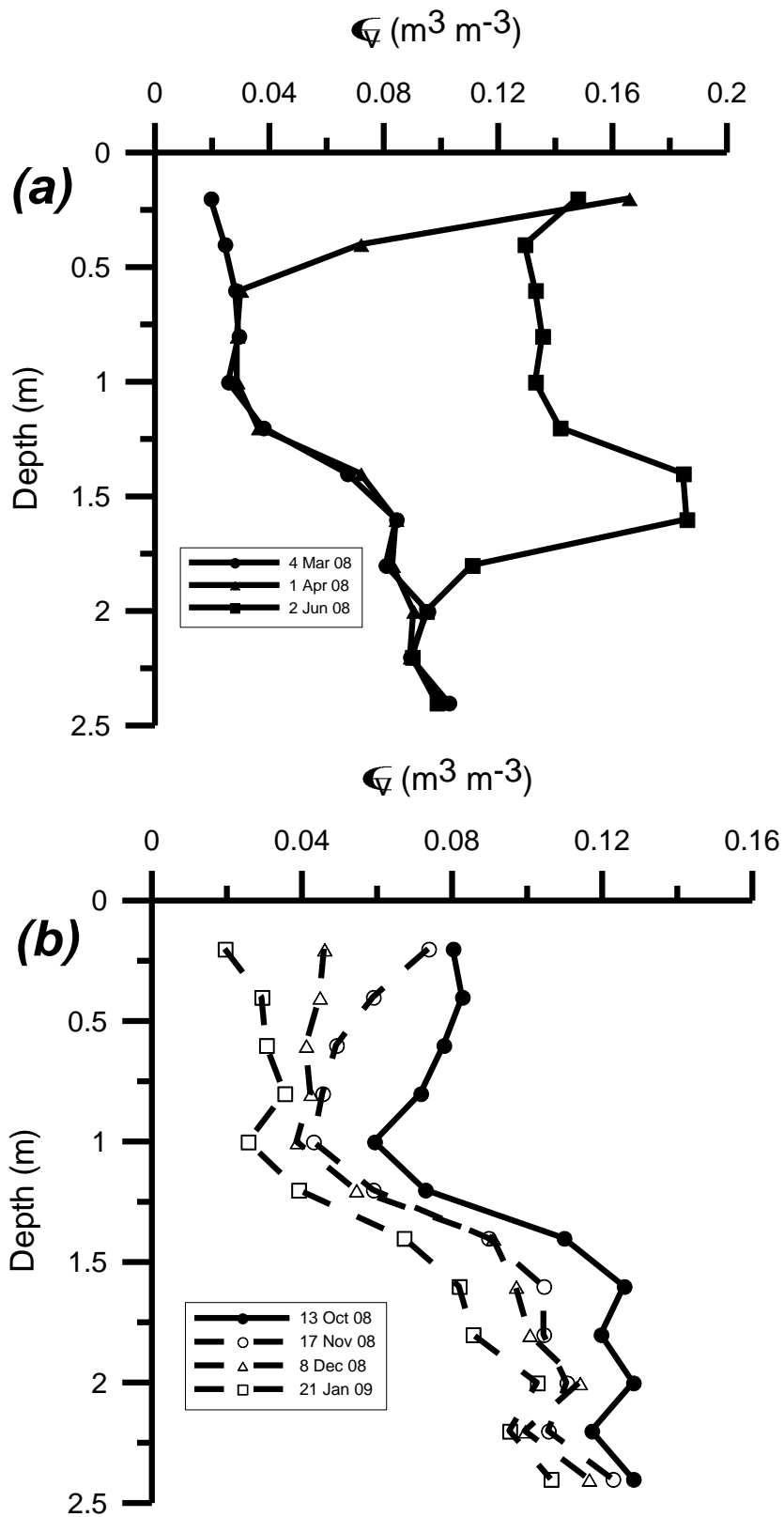


Figure 5. Comparing θ_v determined using NMM over (a) two wetting events and (b) three drying events.

Table 1. Comparison of linear regressions between neutron moisture probe count ratio and θ_v from various sources (after Ruprecht and Schofield 1990)

Institute of Hydrology UK	Silt, sand and gravel	$\theta_v = 0.790CR - 0.024$
	Loam	$\theta_v = 0.867CR - 0.016$
	Clay	$\theta_v = 0.958CR - 0.012$
CSIRO (Bannister)	Sand – Silty clay	$\theta_v = 0.65CR - 0.09$
	Gravel – Tight clay	$\theta_v = 0.55CR - 0.12$
CSIRO (Collie)	Clay	$\theta_v = 0.61CR - 0.12$
	Gravel	$\theta_v = 0.30CR - 0.003$
Del Park (Rupecht and Schofield 1990)	Sand/gravel	$\Delta\theta_v = 0.80\Delta CR$
	Silt	$\Delta\theta_v = 0.82\Delta CR$
	Clay	$\Delta\theta_v = 1.07\Delta CR$
Del Park (Croton and Raper 1996)	Clay and silt	$\theta_v = 0.58CR - 0.05$