Design Aspects of Neutron Moisture Cone Penetrometer

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Abstract

With the ever increasing demand for the utilization of ground with undesirable soil properties, e.g., underground space and reclaimed land, it is challanging for the geotechnical engineers to obtain as accurate information, of the subsurface soil, as possible.   Keeping this aim in mind authors have examined various methods employed to measure various soil properties.   The present paper describes the efforts to combine two different technologies, namely, cone penetration technology and the use of neutrons in moisture measurements, into one.   To this end various neutron sources and nuclear detection system have been examined.   A comprehensive design concept is also described.   Authors have shown that the designed neutron moisture cone penetrometer is a versatile instrument and well capable of measuring various soil properties.

1. Introduction

A neutron moisture gauge is an instrument with a fast neutron source and a slow neutron detector, which measures the moisture content of the or any other medium in terms of the detector count rate, after relating this count rate to the moisture content of the medium by calibration.   The flux of slow neutrons in the vicinity of the detector is determined mainly by the hydrogen present in the vicinity in the form of the water.   Therefore, this technique could be used to measure the moisture content of the medium.

The advantage of this technique is that it is non-destructive; measurements can be made in-situ and can be repeated.   It is rapid, the instrument is portable and it is economical in the long run.

The basic aim of this paper is to summarize the concept of designing, basic phenomenon involved and how the available information is used in the designing of the cone penetrometer and its application in the field of geotechnical engineering.

2. Classification of Neutrons

Sir James Chadwick in 1932, working with the α-particles found that when α-particles were bombarded on beryllium, in contact with paraffin, found that the protons could be detected on the surface of the paraffin block, however, once this paraffin blocks were removed these protons were not detected.   Sir Chadwick deduced from this experiment that neutral particles were formed by the α-reaction on beryllium, and these were able to eject protons from the paraffin block by collision,

Table 1. Classification of neutrons based on their energy level

Thermal Neutrons	E = 0.025 eV
Epithermal Neutrons	E = 1 eV
Slow Neutrons	0.03 eV < E < 100 eV
Intermediate Neutrons	100 eV < E < 10 keV
Fast Neutrons	10 keV < E < 10 MeV
High Energy Neutrons	10 MeV < E

and called these particles neutrons. Therefore, the interaction and moderation of neutrons by hydrogen atoms was inherent in the discovery of the neutron itself. However, neutron moisture meters, which are based on this principle, were developed only in last 40 years or so in order to speed up the soil moisture measurement during the construction of airfields, road and buildings etc.

Neutrons are usually classified according to either their energy level or the velocity. Though the boundaries among various energy levels are drawn arbitrarily, nonetheless, it gives an overview of various terminology which we may encounter in the following discussion. A comprehensive classification according to energy level is given in **Table 1**.

Moisture measurements are based on physical laws govering the scattering and moderation of neutrons. When a source of fast neutrons is replaced in a soil, the neutrons collide with the nuclei of the surrounding atoms and are scattered randomly in all directions. Each collision by a neutron causes a loss of part of its kinetic energy. The scattering and energy reduction process continues for a neutron until its kinetic energy approaches the average kinetic energy of atoms in the scattering medium. The average energy loss by a fast neutron is much greater in collisions with atoms of low atomic weight than in collisions involving heavier atoms. The average number of collisions necessary to thermalize 2 MeV neutrons are given in **Table 2** for certain elements. The loss of energy in a number of collisions depending mainly of the atomic weight, is thus a measure of moderating properties of the nuclei in the given medium.

3. Physical Phenomenon Involved in Neutron Moisture Probe

All the neutron moisture probe contains a source of fast neutrons and a detector of thermal or epithermal neutrons (see **Table 1**). Fast neutrons emitted from the source successively undergo the process of slowing down, thermalization and diffusion. The process of slowing down from the initial energy to the epithermal (1 eV) or

Table 2. Average number of collisions required for fast neutrons (2 MeV) with different elements to reach thermalization state

Elements	Ave. Number of Collisions	Elements	Ave. Number of Collisions
Hydrogen (H)	18.20	Silicon (Si)	262.0
Lithium (Li)	69.30	Phosphorous (P)	288.0
Beryllium (Be)	88.10	Sulphur (S)	298.0
Boron (B)	104.5	Chlorine (Cl)	329.0
Carbon (C)	115.4	Potassium (K)	362.0
Nitrogen (N)	133.5	Calcium (Ca)	371.0
Oxygen (O)	152.0	Titanium (Ti)	442.0
Sodium (Na)	215.0	Manganese (Mn)	504.0
Magnesium (Mg)	227.0	Iron (Fe)	514.0
Aluminium (Al)	251.0	Cadmium (Cd)	1028.0
		Uranium (U)	2169.0

thermal energy (0.025 eV) is governed mainly by the elastic collisions with the hydrogen nuclei, which are considered as free. The subsequent slowing down process, known as thermalization, is a complicated one as it depends on the nature of chemical bonding of the hydrogen. Neutrons undergo thermalization until they attain thermal equilibrium with the medium. Once the neutrons have reached thermal equilibrium with the medium their further migration could be treated as the diffusion of gases, except that the life time of the neutrons is limited by absorption.

The presence of various elements in the soil other than the hydrogen is of minor importance in the slowing down process. Nonetheless, neutrons do undergo collisions with nuclei of these elements in the vicinity of the source and their migration is impeded, therefore, the mean distance between the source and the point at which the neutrons reach epithermal energy depends not only on the hydrogen content (or equivalent water content), but also upon the composition of the water containing matrix. However, for most soils it is mainly, beside moisture content, the dry bulk density that determines this distance and thus the chemical composition of the soil is less important (Zuber and Cameron[1)]).

As stated above, the thermalization process is very complicated and for most of the soils the differences in slowing-down properties of hydrogen in dry soil and hydrogen in soil are unfortunately unknown. Furthermore, as the thermalization process contributes only slightly to the whole slowing down process, it may be assumed that in practice for most soils these differences are negligible. We may observe some differences in soils with a high organic content and bound water, unfortunately no quantification is known to the authors.

Diffusion of thermal neutrons depends mainly upon the content of hydrogen and elements with a high neutron absorption probability and on the dry bulk density and to a lesser degree on the chemical bonds of hydrogen and the overall chemical composition of the soil The higher the content of hydrogen and other non-absorbing

elements, the shorter is the distance migrated by thermal neutrons and the higher their density in the vicinity of the source.   The presence of the neutron absorbing elements in the soil, on the other hand, decreases the thermal neutron density in the vicinity of the source.

4. Neutron Sources

Neutrons are utilized in active methods to provoke a variety of reactions from the soil being examined.   The response of nuclei present in the soil to the irradiation may be identified via neutrons whose properties have been altered by scattering or by induced radiations (mainly gamma rays) characteristic of the reaction occurring. Neutrons may be introduced into the media from one of the following sources: 1. isotopic sources; 2. spontaneous fission sources; or 3. neutron generators. The design considerations include neutron energy, fluence, and the temporal characteristics of the source.   Furthermore, selection of an appropriate source is essential to a successful experimental result (Russell and Oliver[2]).

4.1 Isotopic sources

The principal isotopic sources of neutrons for in-situ investigations result from (α, n) reactions in which the α-particles from a naturally-occurring or artificially produced radioisotope react with the nuclei of suitable low-Z elements.   **Table 3**

Table 3. Various (α,n) isotopic sources with ^{252}Cf spontaneous fission source

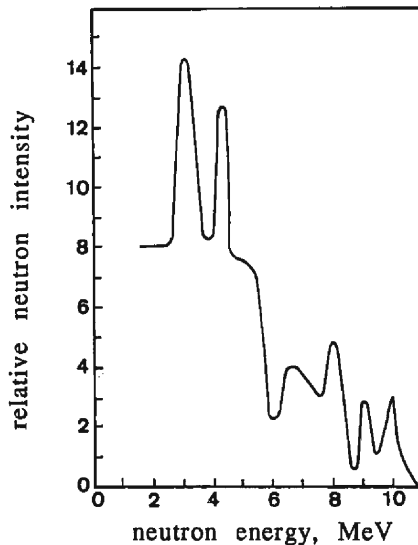| Source	Neutron Yield $(nsec^{-1} GBe^{-1})$	Ave. Energy (MeV)	Half-life
^{241}Am-Be	6.0×10^4	4.0	433 years
^{241}Am-Cm-Be	1.6×10^6	4.0	163 days
^{210}Po-Be	6.8×10^4	4.3	138 days
^{239}Pu-Be	5.4×10^4	4.5	24,360 years
^{227}Ac-Be	5.4×10^4	4.0	21.8 years
^{252}Cf spontaneous fission source			
^{252}Cf 2.34×10^{12} nsec^{-1} gm^{-1} 2.3 1.2×10^8 nsec^{-1}GBq^{-1} 3.5 nfission^{-1}			2.65 years

Fig. 1. Neutron spectrum of [241]Am-Be (α,n) source (Russell and Oliver[2]).

shows some commonly available sources, also listed are some of their characteristics. Isotopic sources have the advantages of being small in size, reasonable cost, availability and reliability. Demerits of using isotopic sources can be summarized as they are limited in the fluence, energy and control. **Fig. 1** shows the neutron spectrum of one the neutron sources listed in the **Table 3**.

4.2 Spontaneous Fission Sources

Spontaneous fission of some transuranic nuclides can be utilized to produce strong source of energetic neutrons. Among these [252]Cf is probably the most commonly encountered source. Some of its properties are listed in **Table 3**. **Fig. 2** shows the neutron spectra of [252]Cf. 1 mg to 10 mg of [252]Cf neutron sources typically yield fluence rates of 2×10^9 sec^{-1} to 2×10^{10} sec^{-1}, resulting in a small, more intense source than (α, n) types. The disadvantage of using [252]Cf as a neutron source is its relatively short half-life. Since it gives a more intense source than (α, n) types, it was decided to use this as the source of fast neutrons. The [252]Cf source used for the purposes of Neutron Moisture Cone Penetrometer is doubly encapsulated in a welded stainless-steel capsule. Its α-decay half-life is 2.73 years and the effective half-life is 2.65 years and the average neutron energy of the [252]Cf-fast neutron source is about 2 MeV (Radiochemical Centre[3]).

4.3 Neutron Generators

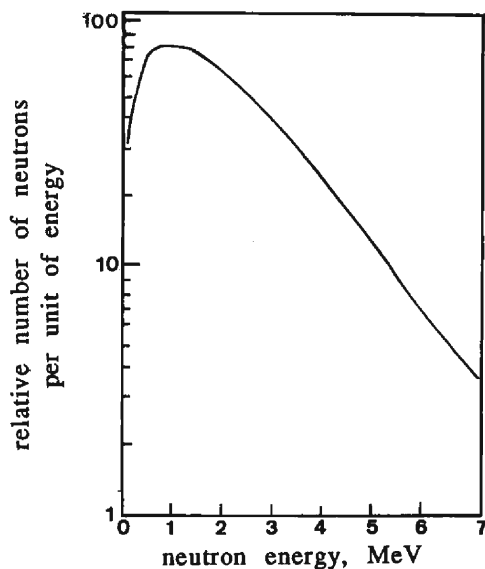Neutron accelarators are used as controllable sources of high energy neutrons

Fig. 2. Fission neutron spectrum of ^{252}Cf source (Russell and Oliver[2]).

for in-situ and laboratory measurements. Borehole generators have been developed which produce 14 MeV neutrons with instantaneous fluence as great as 10^{11} sec^{-1} (Russell and Oliver[2]). As we are not interested in such high level yield, we shall restrict our dicussion to the comments made above.

5. Neutron Detection

Nuclear detection is accomplished basically by three methods, they are

1. ionization chamber;
2. proportional tubes; and
3. Geiger-Meuller tube, however, we shall restrict ourselves to variours types of proportional tubes.

The proportional counter is a type of gas-filled detector which was introduced in the late 1940's. In common with the Geiger-Meüller tubes, proportional tubes, almost always, are operated in the pulse mode and rely on the phenomenon of *gas multiplication* to amplify the charge represented by the original ion pairs created within the gas.

5.1 Regions of Detector Operation

The differences between various types of gas counters operated in pulse mode are illustrated in **Fig. 3**. The amplitude of the observed pulse from the detector is plotted versus the applied voltage or electric current within the detector. At very low values of the voltage, the field is insufficient to prevent recombination of
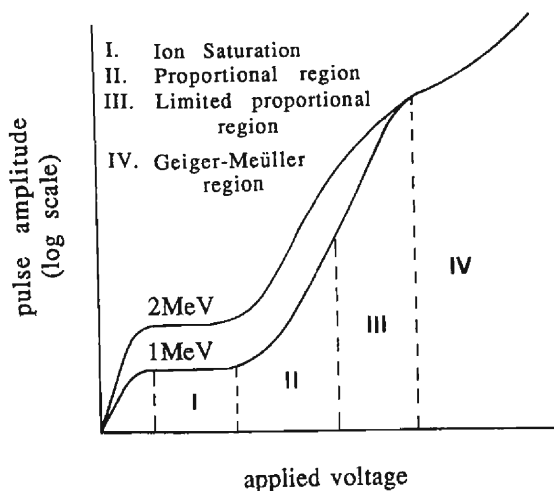
I. Ion Saturation
II. Proportional region
III. Limited proportional region
IV. Geiger-Meüller region

Fig. 3. Different regions of operation of gas-filled detectors (Glasstone[4]).

the original ion pairs, and the collected charge is less than that represented by the original ion pair. As the voltage is raised, recombination is suppressed and the region of the ion saturation is achieved, which is normal mode for the operation of the ionization chamber. As the voltage is further increased, the threshold field at which gas multiplication begins is reached. The collected charges then begin to multiply, and the observed pulse amplitude will increase. Over some region of the electric field, the gas multiplication will be linear, and the collected charge will be proportional to the original number of ion pairs created by the incident radiation. This is the region of *true proportionality*, and represents the mode of operation of conventional proportional counters.

Increasing the applied voltage or electric field further can introduce non-linear effects. The most important of these is related to the positive ions which are also created in each secondary ionization process. Although the free electrons are quickly collected, the positive ions move much more slowly and, during the time it takes to collect the electrons, they barely move at all. Therefore, each pulse within the counter creates a cloud of positive ions, which is slow to disperse as it drift towards cathode. If the concentration of these ions are sufficiently high then they represent a space charge which can significantly alter the shape of the electric field within the detector. Because further gas multiplication is dependent on the magnitude of the electric field, some non-linearities begin to appear. These effects mark the onset of the region of *limited proportionality* (**Fig. 3**) in which the pulse amplitude still increases with increasing number of initial ion pairs, but not in linear fashion.

If the applied voltage is made sufficiently high, the space charge created by the positive ions can become completely dominant in determining the subsequent pulse history. Under these conditions, the avalanches proceeds until sufficient number of positive ions have been created to reduce the electric field below the point at which
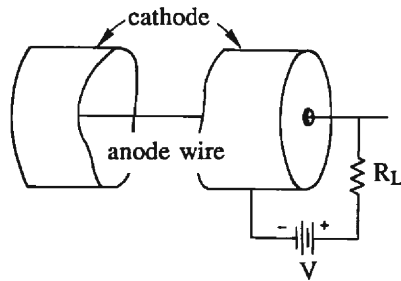
Fig. 4. Basic elements of proportional counter.   The outer cahtode provides a vacuum tight
enclosure for the fill gas.   The output pulse is developed across the load resistance
(Knoll[5]).

additional gas multiplication can take place.   The process is then self limiting, and
will terminate when the same total number of positive ions have been formed
regardless of the number of initial ion pairs created by the incident radiation.   Then
each output pulse from the detector is of the same amplitude, and no longer reflects
any properties of the incident radiation. This is the Geiger-Meüller region cf operation.

Proportional regionality is best obtained by using a cylindrical chamber, which
acts as the negative electrode or cathode, with a central wire acting as the positive
electrode or anode (**Fig. 4**).   When the voltage is high enough the potential gradient
(or the electric field strength) near the central wire becomes so large that the electrons,
produced in the primary ionization of the gas by α or β- particles will move toward
it with a very high speed.   In this proportional region the speed becomes so high
for the electrons to cause the ionization of other atoms and molecules in the gas; the
electrons so produced may cause further ionization and so on (Glasstone[4]).
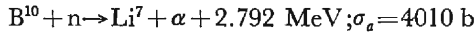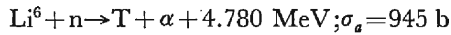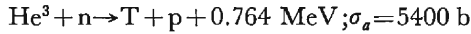
Neutrons are detected through nuclear reactions which result in energetic charged
particles such as protons, alphas, and so forth.   In searching for the nuclear reactions
that might be useful in neutron detection, several factors must be considered.   First,
the cross-section for the reaction must be as large as possible so that efficient detectors
can be built with small dimensions.   In many applications, intense fields of gamma
rays are also found with neutrons and the choice of reaction bears on the ability to
discriminate against the gamma rays in the detection process. Of principal importance
here is the Q-value of the reaction which determines the energy liberated in the re-
action following neutron capture.   The higher the Q-value, the greater will be the
energy given to the reaction products, and the easier will be the task of discriminating
against gamma ray events using simple amplitude discrimination (Knoll[5]).

## 5.2   Reactions Involved in Neutron Detection

Since the neutrons do not react appreciably with electrons, they are always
detected through effects caused by their collision with nuclei.   Almost every type of
nuclear interaction of neutrons results in a directly observable effect which may be
used in the detection of neutron.

Various interactions have been proposed for the detections of the neutrons, e.g., elastic scattering, exothermic reactions, fission, and radiative capture. We shall restrict our discussion to exothermic reactions only.

For the detection of slow neutrons exothermic reactions in which protons or α-particles are produced have been widely used. Exothermic reactions of this type that have large cross-section at low energies are:

$$\text{He}^3 + \text{n} \rightarrow \text{T} + \text{p} + 0.764 \text{ MeV}; \sigma_a = 5400 \text{ b}$$

$$\text{Li}^6 + \text{n} \rightarrow \text{T} + \alpha + 4.780 \text{ MeV}; \sigma_a = 945 \text{ b}$$

$$\text{B}^{10} + \text{n} \rightarrow \text{Li}^7 + \alpha + 2.792 \text{ MeV}; \sigma_a = 4010 \text{ b}$$

Also given at the end of each reaction is the cross-section for a neutron velocity of 2200 m sec^{-1}. In the above stated reactions He, Li, B, and T stands for helium, lithium, boron and tritium respectively. n, p, and α are neutron, proton and alpha particles respectively. Energy is given in million electron volts (MeV) and the reaction cross-section (σ_a) is given in barns (b). Another reaction of this type which has been proposed for the detection of neutrons but with much smaller cross-section is

$$\text{N}^{14} + \text{n} \rightarrow \text{C}^{14} + \text{p} + 0.627 \text{ MeV}; \sigma_a = 1.75 \text{ b}$$
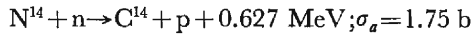
In this reaction N is nitrogen, C is carbon and other symbols have same meaning as described above. The disintegration cross-section of He^3, Li^6, and B^{10} is shown in **Fig. 5.**

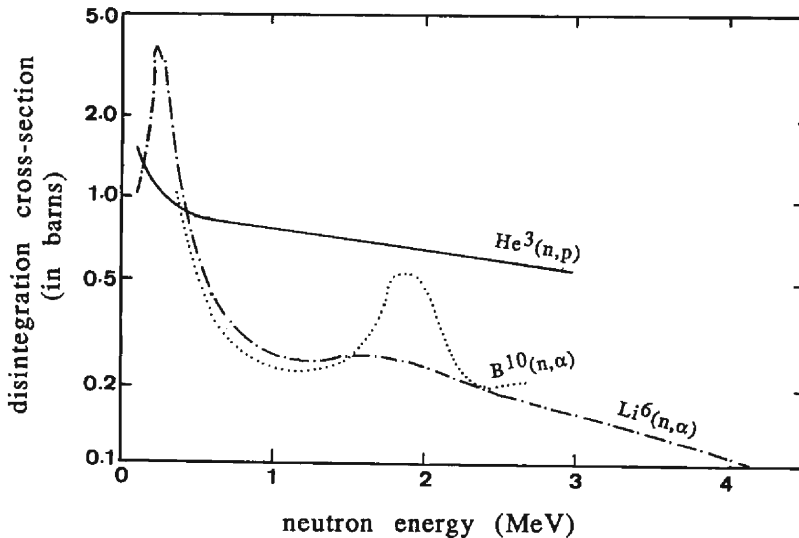The desirable properties of the He^3(n, p) T reaction are smooth variation of the

Fig. 5. The cross-sections for the disintegration of He^3, Li^6, and B^{10} as a function of neutron energy (Barshall[6]).

cross-section with energy, the absence of excited states of T resulting in a fixed kinetic energy of the reaction products for given neutron energy, the absence of other neutron-induced reaction producing charged particles. The fact that the He^3 is a gas which is suitable for use in counter allows the construction of detectors of high efficiency. The $Li^6(n, \alpha)$ reaction, on the other hand, lacks some of these desirable properties. The cross-section exhibits a high peak at a neutron energy of 0.25 MeV and perhaps another anomaly at a neutron energy of 1.5 MeV. Since no gaseous compound of lithium (Li) suitable for filling the counter is available, it is not conveniently possible to prepare counters of high detecting efficiency. An advantage of $Li^6(n, \alpha)$ reaction is its high reaction energy, which helps to distinguish reaction products from recoils and γ-ray induced events. For the observation of disintegrations Li^6 has been embedded in photographic emulsions for the purpose of studying neutron spectra.

The $B^{10}(n, \alpha)$ reaction has been used most widely for the detection of slow neutrons. The high cross-section of the reaction at the thermal energies, the availability of B^{10} either in ordinary form (boron) of which it constitutes almost 20% or isotopically separated, and the existence of both soild and gaseous compounds are responsible for the wide use of B^{10}. The gaseous compound which is suitable for filling in the counter is BF_3. While BF_3 is commercially available, the purity of commercial grade BF_3 is frequently not high enough for satisfactory counter operation.

The (n, α) cross-section of B^{10} is inversely proportional to the neutron velocity at the lowest energies, but deviates from this relationship at a few hundred keV. A marked peak in the cross-section occurs at 1.9 MeV. At thermal energies only 6.5% of the disintegrations produce Li^6 in its ground state, most of the disintegrations leading to the 0.48 MeV excited state of Li^6.

Although the $N^{14}(n, \alpha)$ reaction was proposed for the application in neutron spectroscopy, this reaction has not proven to be suitable beacuse of the rapid variation of the cross-section with energy which is caused by energy levels in N^{15}. Furthermore, the $N^{14}(n, \alpha)$ reaction complicates the energy distribution of the disintegration products. The $B^{10}(n, \alpha)$ Li^6 reaction suffers from the difficulty of the production of Li^6 nuclei in the excited state. Some success in measuring neutron energy distribution has been achieved with Li loaded photographic emulsions (Barschall[6]). However, the best results have been obtained with the He^3-filled proportional tube.

Above going discussion lists various desirable and undesirable properties of various reactions involved in the detection of slow neutrons. In a glance we can see that the He^3-filled proportional tubes have more desirable properties than undesirable properties compared with other reactions involved in the detection of slow neutrons. It was thus decided to use this as the detection system for the slow neutrons.

In the preceeding paragraphs we have discussed some of the desirable properties of He^3-filled proportional tube, what follows hereafter is the listing of some of the characteristics of the He^3-filled proportional tube employed in the neutron moisture cone penetrometer to detect slow neutrons (also see **Photo. 1**):
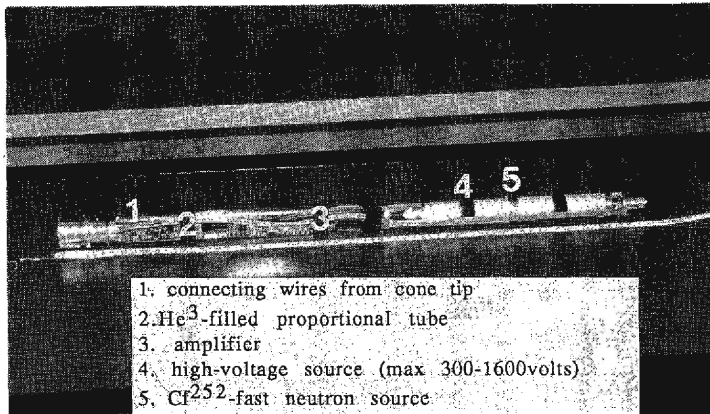
1. connecting wires from cone tip
2. He^3-filled proportional tube
3. amplifier
4. high-voltage source (max 300-1600 volts)
5. Cf^{252}-fast neutron source

Photo. 1. Details of the assembled unit.

a. Wall characteristics
   1. thickness$=0.081$ cm
   2. effective length$=20.32$ cm
   3. outside diameter≤ 2.54 cm
   4. material$=1100$ Al
b. Tube dimensions
   1. maximum diamter$=2.62$ cm
   2. maximum overall length$=26.0$ cm
c. Other characteristics
   1. gas filling$=He^3$
   2. gas pressure$=304$ cm Hg^{-1}
   3. operating voltage$=1275$ volts
   4. weight$=5$ oz.
   5. operating temperature range$= -50°C$ to $+100°C$

Another aspect which authors feel worth mentioning is optimum measuring time that a detector should have. Based on the data compiled by the IAEA[7], it was concluded that the optimum measuring time is less dependent on the moisture content than the number of counts (N). Therefore, a pre-set time is more suitable than a pre-set count. In the case of designed penetrometer the pre-set time for the measurement is one second.

6. Application of the Neutron Moisture Cone Penetrometer

6.1 Calibration of the Neutron Moisture Cone Penetrometer

Utilizing the ideas gained above, authors have developed a so-called neutron moisture cone penetrometer, which is not only able to measure the cone penetration resistance (q_c), sleeve friction (f_s), excess pore pressure (u), but can also measure the

natural water content (w) of the soil. **Fig. 6** shows the schematic view of the neutron moisture cone pentrometer. **Fig. 7** shows the calibration curve as obtained in the laboratory. The materials used in the laboratory have been mountain sand, fine and coarse pebble. As it was difficult to prepare a homogeneous clay sample it was decided to carry out the field testing based on the calibration curve obtained in the laboratory. However, it gave moisture content values lower than the values obtained in the laboratory testing. Nonetheless, while carrying out the penetration testing, beside measuring q_c, f_s, u and w, density of the soil has also been calculated. Inserting those values and back calculating we may obtain new calibration curve
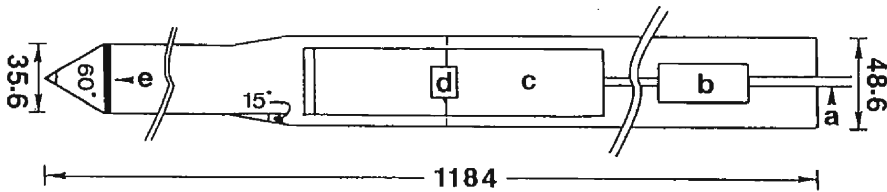
a: cable leading to data collection system
b: pre-amplifier + high voltage source
c: ^{3}He-filled proportional tube
d: ^{252}Cf fast neutron source
e: ceramic porous filter
(all dimensions in mm)

Fig. 6.   The schematic diagramme of the Neutron Moisture Cone Penetrometer.
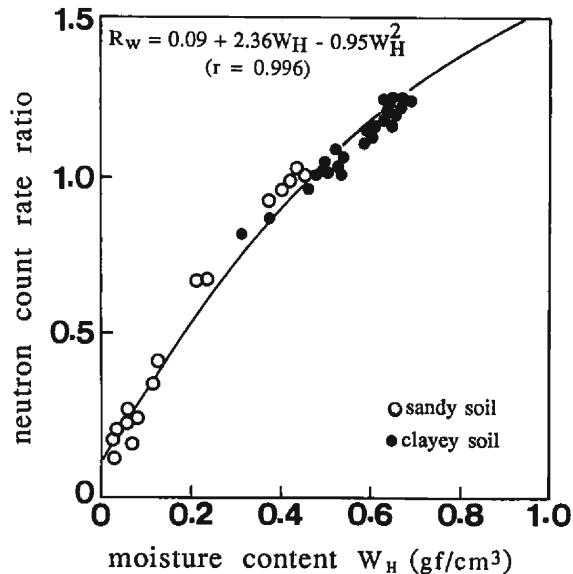

Fig. 7.   Modified laboratory calibration curve after inserting the data for clayey soil obtained from in-situ testing.

which is shown in **Fig. 8.** There are other factors which may effect the shape of the calibration curve. Among them probably the most important is the spacing bet-ween the source and the detector. **Fig. 9** and **Fig. 10** show two different examples. BF$_3$-filled proportional counters had been used in detecting the slow neutrons. As the slow neutron flux is maximum at the source, the highest efficiency for a given counter is obtained when the source is placed in the middle of the counter. Further-more, if the detector is very shoit, the calibration curve is concave to the count rate axis. When the detector length increases, the calibration curves first become approximately lineai and eventually become convex to the count rate axis. The curves number 2 and 5 shown in **Fig. 9** are typical of those with central source geo-metry and shown in the inset is a simple geometry of a detector and the source position relative to the detector length which gives a near linear calibration curve.
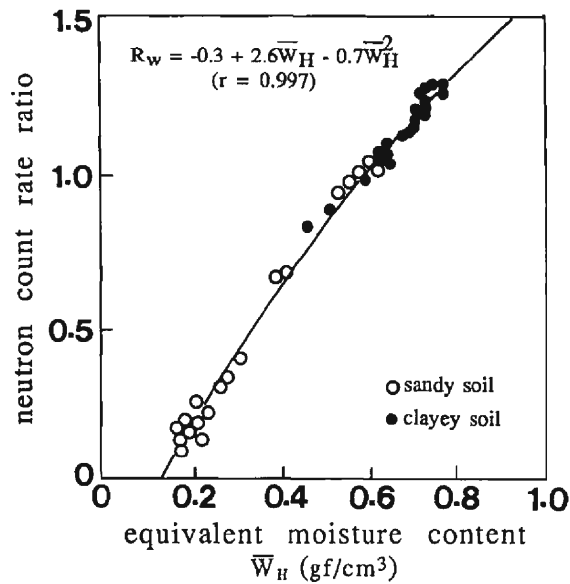

$$R_w = -0.3 + 2.6\overline{W}_H - 0.7\overline{W}_H^2$$
$$(r = 0.997)$$

○ sandy soil
● clayey soil

equivalent moisture content
$\overline{W}_H$ (gf/cm^3)

neutron count rate ratio
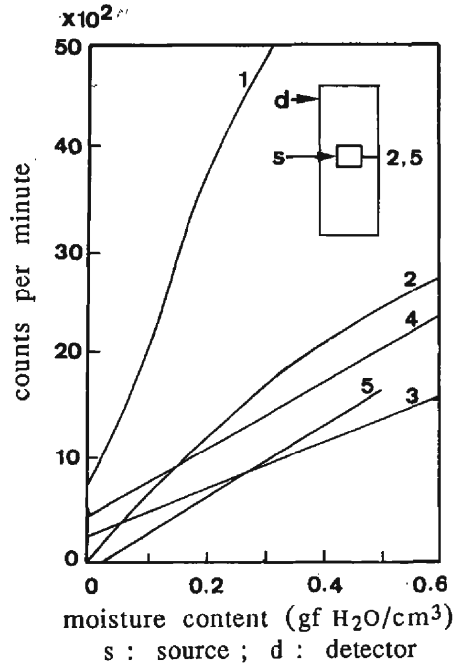
Fig. 8. Calibration curve after density correction.

Fig. 9. Calibration curves for different commercially available neutron moisture gauge (Zuber and Cameron[1]). (Sources are set at the center of the detectors for curves 2 and 5, whereas other curves indicate the relations when sources are not set at the center of the detector.)
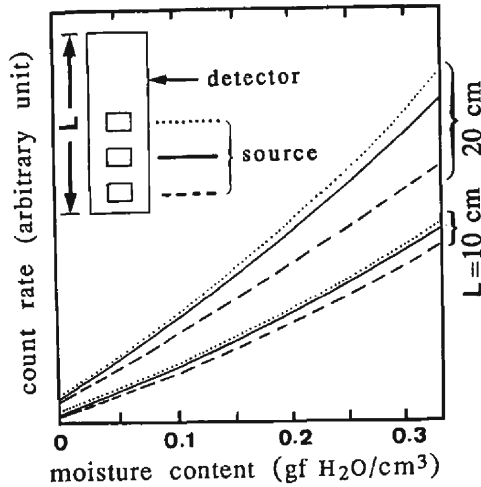

Fig. 10. Calibration curves for different geometries.

6.2 Field Application of Neutron Moisture Cone Penetrometer

Neutron moisture cone penetrometer may be used for measuring the moisture

profile of the soil alongwith other soil parameters, such as, q_c, f_s, and u.   It may also be used for calculating the long term settlement etc.   In this section we shall not present the details of the field testing, however, **Fig. 11** and **Fig. 12** show some typical results obtained by using the neutron moisture cone penetrometer.   In-situ testing was carried out by means of a 1-ton hydraulic system.   In the case of sandy ground where the q_c value is rather high, counter weight is placed on the foot of the platform to off-set the negative reaction produced by penetration.   The penetration rate was kept constant at 2 cm sec^{-1}.   For details of these testing see Shibata et al.[8] and Shibata et al.[9].
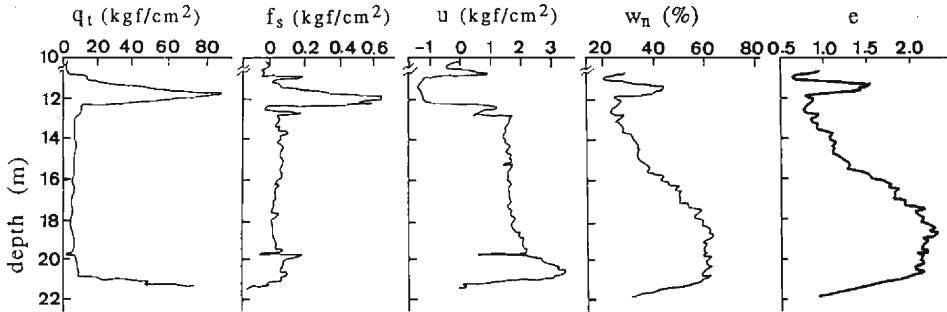

Fig. 11. Data obtained using the neutron moisture cone penetrometer at the Koshien site (Shibata et al[9]).
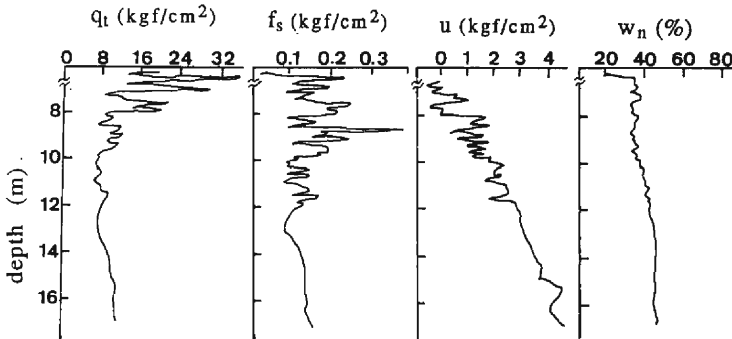

Fig. 12. Data obtained using the neutron moisture cone penetrometer at the Umeda site (Shibata et al.[9]).

6.3   Factors Influencing the Neutron Moisture Measurements

Various factors may influence the neutron moisture measurements, such as the dry bulk density, concentration of elements with high neutron absorption probability, bound water content, temperature, distortion caused by the penetration of the soil etc.   The influence due to dry bulk density, and the concentration of high neutron absorbing elements are discussed by Shibata et al.[9].   Thereforore, we shall limit

ourselves here to the other listed parameters.

6.3(1) Bound Water Content

As the designed probe use the thermal detector, it is expected that the neutron moisture gauge would measure total water content. It has been pointed out that the reading of these gauges are often independent of, or only slightly dependent on, bound water content for many soils. This has shown to be due to some accidental correlation between bound water content and concentration of elements with large σ_a. With the exception of chlorine which is found in marine deposits or saline ground water, the others occur mainly in clay minerals, and therefore, some correlation would be expected. It has been pointed out that due to this correlation, the differences between calibration curves for different soils are not great and, in consequence, one calibration curve can be applied to many soils. This can be done if the required accuracy is low, however, if high accuracy is required then one calibration is insufficient (Zuber and Cameron[1]).

6.3(2) Temperature

An increase in temparature of the soil decreases the neutron density in the vicinity of the source and decreases the apparent water content indicated by the gauge. However, Olgaard[10] has shown that the temperature effect is of little importance at small moisture concentrations, it may be significant at high moisture contents.

6.3(3) Distortion Caused by the Penetration of Soil

Though the distortion caused by the penetration of the soil is less than the disturbances caused by drilling. However, no quantification is available at the moment. Authors are at the moment preparing to study this phenomena and how does this disturbance affects the neutron moisture measurements.

7. Conclusion

Authors have tried to put togther various desigen aspects that went into the designing and the development of the Neutron Moisture Cone Penetrometer. Some of the examples from actual in-situ testing have been preseated. It has been shown that the neutron moisture cone penetrometer is a versatile instrument, which can not only measure the moisture profile of the soil but also is capable of measuring cone resistance, excess pore pressure, and sleeve friction. Its advantages are economical in the long run as the boring and securing the bore holes shall not be required. Reliability and repeatibility is high. The instrument is portable.

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