The proposed sensor design is a capacitive soil moisture sensing that was developed using 304 stainless steel rod arranged as a multi-depth probe. The structure consists of a single shared ground electrode running along the full length of the rod, while each measurement depth (20 cm, 40 cm, and 60 cm) is equipped with an independent sensing electrode. Unlike designs that multiplex a single ADC channel among multiple depths, the proposed architecture employs separate ADC modules for each level, allowing the ESP32 microcontroller to acquire the three level soil moisture readings simultaneously through individual ADC pins without signal interference.

The sensing principle is based on the fact that the dielectric permittivity (ε) of soil increases substantially with volumetric water content. When the soil becomes wetter, the effective capacitance between the shared ground rod and each measurement electrode also increases. This change alters the analog output voltage of each A/D module, enabling volumetric moisture estimation at multiple depths. The capacitance:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

increases sharply when soil becomes wet, because water has a very high dielectric constant ($\varepsilon_r \approx 80$) compared to dry soil ($\varepsilon_r \approx 2$–4) or air ($\varepsilon_r \approx 1$).

And read data from ADC pins by command:

$$\text{Moisture} = \text{map}(ADC, 0{,}4095, ADC_{wet}, ADC_{dry}).$$

Command read data and mapping data to soil moisture value in prototype nodes

```
int soilval1 = analogRead(analogPin1);
Soil20cm = map(soilval1, 0, 4095, 100, 0);
int soilval2 = analogRead(analogPin2);
Soil40cm = map(soilval2, 0, 4095, 100, 0);
int soilval3 = analogRead(analogPin3);
Soil60cm = map(soilval3, 0, 4095, 100, 0);
```

In areas along canal banks, the condition is often soft clay soil, which has characteristics typically high water retention, low permeability, and strong dielectric sensitivity to moisture variation. Capacitive sensors are advantageous in such environments because soft clay exhibits large permittivity shifts even with small changes in pore-water volume. This characteristic improves measurement resolution and stability compared with resistive soil sensors, which often suffer from electrode corrosion and ion-mobility effects in high-moisture clay soils. Consequently, the multi-depth capacitive model provides accurate profiling of water infiltration and is aligned with geotechnical principles governing clay behavior in the vadose zone.

Operating Principle

A capacitive soil moisture sensor does not measure water directly that it measures the **effective capacitance** between two conductive points embedded in soil. The capacitance:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

increases sharply when soil becomes wet, because water has a very high dielectric constant ($\varepsilon_r \approx 80$) compared to dry soil ($\varepsilon_r \approx$ 2–4) or air ($\varepsilon_r \approx 1$).

ϵ = dielectric permittivity
A = cross-sectional area of sensor
d = distance of plate

Thus, increases in soil water infiltration produce higher capacitance values, which **reduce the oscillation frequency or modify the RC charging curve** sensed by the ADC. The microcontroller interprets this as soil moisture percentage after calibration using:

$$\text{Moisture} = \text{map}(ADC, 0{,}4095, ADC_{wet}, ADC_{dry}).$$

Suitability for Soft-Clay Soil

Soft-clay soil is characterized by:

- high plasticity
- slow drainage
- water retention with gradual vertical infiltration
- high ion content (but not enough to affect capacitive sensing)

These characteristics make capacitive sensing preferable to resistive (conductive) sensing because:

- **Resistive sensors fail quickly** due to electrode corrosion from ionic soil water.
- **Capacitive sensors do not conduct DC current through soil**, and therefore last years even in high-moisture clay.
- Clay's stable dielectric structure allows **clear distinction between water layer changes**, especially across 20–60 cm depth.

Additionally, using a multi-depth probe allows monitoring of **infiltration fronts**, useful for irrigation and flood-response applications.

Measurement Flow

1. MCU excites the selected electrode.
2. The surrounding soil acts as the dielectric medium shaping the effective capacitance.
3. The RC response is digitized by the ESP32 ADC.
4. Three depth values are acquired in sequence every sampling period.
5. The LoRa node transmits calibrated moisture percentages to the gateway.