Soil/Backfill Thermal Resistivity

WIND-FARM PROJECTS
RENEWABLE Energy Program has resulted in a huge increase in the number of wind-farm projects commissioned over the past 5 years.

It is quite common to encounter relatively dry soil condition (windy and arid) and rock outcrop at shallow depths.

Relatively high soil thermal resistivity (see case studies).

Presence of shallow rock outcrop makes trenching/construction slow and expensive.

Trench/cable route lengths are fairly long and covers large areas.

Depending on the configuration/design, cables from numerous turbines are installed in a common trench.

Result: Although the cables operate at lower voltage, the mutual heating and heat-flux per unit length is high.
WIND-FARM

Each turbine is a ‘power plant’ with generation leads

Load pattern is significantly different from that of normal T&D cables (peaks and buffers)

Relatively high loads for long periods

Must not be treated as ‘distribution’ cables because of the low voltage

Cable burial depths are relatively shallow (3 ft) and therefore the earth ambient temperature can be high (end of summer)

Assumption of ‘low’ soil thermal resistivity (~90°C-cm/W) can and has resulted in premature failure

Short-cuts in trenching, installation and backfilling is a major problem because most contractors do not understand (or ignores) the importance of the thermal environment
WIND-FARM

Trenching, installation and backfill: Automated, single operation to plough and lay cables and to backfill with native soil is acceptable only if the resultant thermal dryout characteristic is used for the rating.

Cable Spacing: Vertical, horizontal, single or multiple, burial depth, etc. must be taken into consideration.

Backfill: Almost all cable are directly buried and therefore, native soil in most cases may not be acceptable to use as backfill. The cohesive nature will make it difficult to reinstate it to its natural condition. Presence of coarse particles (gravel) may pose a serious problem – damage the cable jacket/insulation.

Common Practice: Use the native soil with minimum or no compaction (dump it over the cables) and relay on the rain and natural settlement process to attain a density similar to the in-situ condition. This may happen but not within a few months or years.
Corrective Backfill: It is not a problem if the native soil is suitable and if it is installed at the correct density.

Because of the remote location, it may not be practical to import backfill material. In such cases, the native soil can be modified by mixing with other local material or in some cases, simply ‘wetting’ it to improve its mechanical/thermal characteristic.

If the native soils are granular (non-cohesive) a simple process to ‘fluidize’ may offer an acceptable solution.

This is currently being implemented on a project in Texas and is found to be very cost-effective.

Comments: The rating must be based on the measured parameters of the thermal environment of the cables (temperature as well as the thermal resistivity; taking into consideration the moisture condition.)
EXTERNAL THERMAL ENVIRONMENT
Effect of Soil Thermal Resistivity on the Cable Ampacity

• cables are buried directly in native soil without the presence of any special thermal backfill

• effect and importance of soil thermal resistivity on cable ampacity

• actual ampacity numbers vary but relationship holds true for any type of cable system

• number of options to improve overall thermal performance of cable environment
EXTERNAL THERMAL ENVIRONMENT

In order to improve the thermal performance of the external thermal environment, an envelope of an imported material commonly referred to as controlled backfill or corrective thermal backfill is installed around the cables. The thermal characteristic of this material and the thickness of the envelope will result in an overall lower thermal resistivity. This new value of thermal resistivity – composite resistivity or effective resistivity is used in the ampacity calculations.

Most computer based ampacity programs are capable of handling numerous variables and parameters for native soil, backfill, thickness, trench width, burial depth, spacing, etc.
EXTERNAL THERMAL ENVIRONMENT
Pipe-Type Cable Installation

• cables can be treated as heat source
• ambient earth surface as ultimate heat sink
• controlled backfill, native soil & other backfills as medium through which heat is transported – primarily by conduction

Keeping cable temperatures in design limits under all conditions is key to heat transfer efficiency and stability of external thermal environment between cables and ground surface
HEAT TRANSFER THROUGH SOIL

- Predominantly by Conduction
- Often with Conduction and Convection (Saturated Soils)
- Sometimes with Phase Change
STeady-state radial heat conduction from an underground cable

Consider a cylindrical heat source (power cable) in a homogeneous media (soil).

\[ q = -2\pi \ r \ K \left( \frac{dT}{dr} \right) \quad or \]

\[ \int^{T_1}_{T_2} dT = \frac{q}{2\pi K} \int^{r_1}_{r_2} \frac{dr}{r} \]

The thermal gradients in a radiant flow field are inversely proportional to the distance from the heat source.

Therefore: thermal conductivity of soil adjacent to cables is very important.
CONSIDER A POWER CABLE IN MULTIPLE LAYERED MEDIA

 Thermal gradients in each layer are dependent on the thermal conductivity and the proximity to the heat source.

 This demonstrates the importance of using a high thermal conductivity material around the cable to offset the effects of low thermal conductivity native soil.

\[
T_1 \cdot T_4 = \frac{q}{2\pi} \left[ \int \frac{R_4}{rK_3} dr + \int \frac{R_3}{rK_2} dr + \int \frac{R_2}{rK_1} dr \right]
\]
FACTORS AFFECTING SOIL THERMAL RESISTIVITY

1. SOIL COMPOSITION
   - Mineral Type and Content
   - Organic Content
   - Chemical Bonding Between Particles

2. TEXTURE
   - Grain Size Distribution
   - Grain Shape

3. WATER CONTENT
   - Degree of Saturation
   - Porosity

4. DRY DENSITY
   - Porosity
   - Solids Content
   - Inter-particle Contacts
   - Pore Size Distribution

5. AMBIENT TEMPERATURE
   - Negligible Effect at Normal Temperature Range

6. OTHERS
   - Solutes – Dissolved Salts and Minerals
   - Hysterisis (Leatchets)
DEFINITION AND MEASUREMENT OF IMPORTANT GEOTECHNICAL PARAMETERS OF SOIL

High Thermal Resistivity:
Uniform size soil particles (i.e., Low soil density) provide few contacts for heat conduction.

Low Thermal Resistivity:
Variety of particle sizes (i.e., Well graded) reduces air spaces (i.e., High soil density) and provides many contacts for heat conduction.
DEFINITION AND MEASUREMENT OF IMPORTANT GEOTECHNICAL PARAMETERS OF SOIL

Wet Soil: High water content provides an easy path for heat conduction ("thermal bridges"), therefore the soil thermal resistivity is low.

Damp Soil: As soil dries, discontinuities develop in the heat conduction path due to low water content, therefore thermal resistivity increases.
DEFINITION AND MEASUREMENT OF IMPORTANT GEOTECHNICAL PARAMETERS OF SOIL
SOIL COMPONENTS

<table>
<thead>
<tr>
<th>Description</th>
<th>Thermal Resistivity Dry (°C-cm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil Grains</strong></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>12</td>
</tr>
<tr>
<td>Granite</td>
<td>30</td>
</tr>
<tr>
<td>Limestone</td>
<td>40</td>
</tr>
<tr>
<td>Sandstone</td>
<td>50</td>
</tr>
<tr>
<td>Shale (sound)</td>
<td>60</td>
</tr>
<tr>
<td>Shale (highly friable)</td>
<td>200</td>
</tr>
<tr>
<td>Mica</td>
<td>170</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>45</td>
</tr>
<tr>
<td>Water</td>
<td>165</td>
</tr>
<tr>
<td>Organics</td>
<td>~500</td>
</tr>
<tr>
<td>Oil (petroleum)</td>
<td>~800</td>
</tr>
<tr>
<td>Air</td>
<td>~4500</td>
</tr>
</tbody>
</table>
CORRECTIVE THERMAL BACKFILLS

Material that will enhance the heat conduction

In general the native soils are not used as trench backfills

Imported materials e.g., well graded sands, stone screenings, duct bank concrete and Fluidized Thermal Backfill (FTB) are the most common types of backfill

These are Select Materials, Man-Made and Engineered to Meet Specific Thermal and Mechanical Performance

Some Naturally Occurring Granular Soils, and By-Products of Stone Quarries may also Qualify as Good Backfills
CORRECTIVE THERMAL BACKFILLS

Performance Requirements

Should maintain low thermal resistivity over the expected range of operating conditions, and over a wide range of moisture changes.

Should have a low “critical moisture content” and high thermal stability limits (t/d^2)

Should not have any adverse effects on cable jacket or pipe coating

Should be easy to install, excavate and re-instate

Should be readily available and at a reasonable cost
CORRECTIVE THERMAL BACKFILLS

Types of Thermal Backfills

Native soils if found to be satisfactory (very seldom)

Granular materials
e.g. well-graded sands and stone screenings

Granular soils with additives (binders)

Sand-cement mixtures

Fluidized Thermal Backfill (FTB)
SOURCES OF THERMAL BACKFILLS

Borrow Pits

Blended Soils

Crusher By-Products (Aggregate Processing Plants, Quarries)

Concrete Aggregate Suppliers

Ready-Mix Concrete Plants and Suppliers
SELECTION CRITERIA

Grain Size Distribution (Sieve Analysis)
Clay Faction or Fines Content (≤ #200 Sieve Size Material)
Organic Content
Porosity (Soundness)
Mineral Type (Quartz, Limestone, Granite, Feldspar, Mica)
Compactability (Density – Moisture Relationship)
Thermal dryout Characteristics (T.R. vs M.C.)
Thermal Stability
Availability and Location (From Project Site)
Variability (Limits and Deviations)
Cost
BACKFILL INSTALLATION

Granular Type:

- Moisture Conditioning
- Compaction in Thin Lifts
- Density and Moisture Control

Most Commonly Used Equipment: Plate type vibrators, vibratory rollers, vertical tampers

If the stock-piled material is drier than the optimum moisture content, water should be added and thoroughly blended before placing in thin lifts and compacting.

OR

Material can be placed in thin lifts not exceeding 100mm, and water sprayed uniformly to bring the moisture to the required level prior to compacting.
BACKFILL INSTALLATION

The Density of the Compacted Backfill Depends on:

- Type of Backfill Material
- Moisture Conditioning (Wet or Drier Than Optimum)
- Compaction Energy Per Unit Volume
- Type of Compaction Equipment

Quality Control:

- Moisture content and installed density.

A well implemented quality control program during field installation of backfill is a good insurance against hot-spots and de-rating of cable ampacity.
FLUIDIZED THERMAL BACKFILL (FTB)

Although well designed granular type thermal backfills e.g. Thermal sands and stone screenings have good thermal characteristics, the performance of these materials when installed in cable trench is purely a function of the density and moisture content. This requires strict quality control during the construction phase. This is time consuming and expensive. One other limitation of granular type backfill is that it can not be installed under very wet conditions.

THE IDEAL SOLUTION IS TO USE FTB

A concrete like material that is made of local sands, aggregates, flyash, cement and water.

- Engineered to meet thermal and mechanical parameters
- Yields low and stable thermal resistivity
- Flows freely without segregation

Cont...
Develops adequate strength within 24 hours to allow reinstatement of road surface
Ensures voids free installation
Easy to install, excavate and re-instate
Compatible and accepted for use by other utilities
Road crossings and railway crossings
Urban areas with multiple services
Cable tunnels and conduits
Inside power plants and transformer stations
Steep slopes and shorelines
Can be pumped long distances using conventional equipment
Ideal for hot spot mitigation
FTB DESIGN

Sourcing of component materials from local suppliers of sands, aggregates, flyash. (Quarries, stone and aggregate suppliers and ready-mix concrete suppliers)

Testing of the above for quality and consistency – sieve analysis, mineral type, soundness, porosity, variability

Thorough formulation and testing in the laboratory to optimize the following parameters:

• Thermal – Resistivity and Stability
• Mechanical – rate of hardening and compressive strength
• Flow – Slump and diameter
• Prepare specifications – mix design and performance
QUALITY CONTROL – SUPPLY AND INSTALLATION

Write detailed specifications for quality control testing; include method and frequency of tests (every 100 cu.m. or every 100m of cable trench) procedures for sampling, curing, transportation and testing and reporting of test results.

Describe test equipment and procedures for thermal testing – IEEE standard and ICC guidelines

Select an independent laboratory or contractor specialized in thermal testing

Inspection of stock pile and batch plant

Testing the suppliers mix for approval prior to installation

Conduct a field demonstration for the utility personnel

Sampling and testing during field demonstration and during the course of the project