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The Effect of Underground Cable Diameter on Soil Drying, Soil Thermal Resistivity and Thermal Stability

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***Abstract*—Heat generated by underground cables has been known to cause drying of the surrounding soil. This may change soil thermal resistivity sufficiently to cause cable overheating and subsequent failure. Methods have been used in the past to try to relate the time for soil to dry to the diameter of the cable. These existing methods were shown to be invalid by former experiments. This paper presents the results of an experiment designed to determine if there is a relationship between the diameter of an underground cable and the time it takes soil to dry around that cable. The analysis of the results of the experiment suggested that there is such a relationship and the form that such a relationship may take.**

***Index Terms*—Soil Moisture, Soil Properties, Thermal Conductivity, Thermal Stability, Thermoresistivity, Cable Ampacity.**

I. NOMENCLATURE

Ampacity—Amount of current a cable can conduct without damage due to overheating.

Thermal Resistivity—Bulk property of a material that is a measure of the material's ability to resist the conduction of heat. Measured in cm°C/W.

Thermal Stability—Ability of a material such as soil to maintain its thermal resistivity in the presence of drying due to elevated temperatures.

II. INTRODUCTION

Any cable carrying current will generate heat that must be removed from the cable vicinity or the cable can quickly overheat and sustain damage. The amount of heat generated in the cable is determined by the current and varies with the square of the current. In the case of a cable installed underground there are three mechanisms by which heat is removed from the cable: conduction of heat through surrounding soil, removal of heat by vaporizing soil moisture which then migrates away from the cable, and absorption of heat by the surrounding soil thereby increasing the soil temperature. The first two methods are the most important. Since the cable has a maximum temperature limit, its ampacity will be determined by the rate at which heat is carried away.

The conductive heat rate is dependent upon the thermal resistivity of the soil; the lower the resistivity the faster the heat will be conducted away. The resistivity, in turn, is principally controlled by the amount of moisture in the soil. Higher moisture content results in lower thermal resistivity because water fills in the air voids between soil particles aiding the conduction of heat between particles. In addition to heat conduction, part of the heat is carried away by vaporizing the soil moisture in contact with the cable. This vapor migrates away from the cable thereby drying the soil in contact with the cable. Unless this moisture can be replenished from the surrounding soil quickly enough, the soil in contact with the cable will dry and increase in thermal resistivity. This reduces the conduction of heat away from the cable causing it to overheat.

Some sources have found that rather than changing in resistivity gradually as the soil is heated, it may change suddenly. In some cases a soil may exhibit a wet resistivity value which is constant until a point called the "effective drying time". At that point the soil resistivity quickly increases in value and rapidly attains a dry resistivity value, which may be many times larger than the wet resistivity [1][2]. The same sources also suggest that the time it takes soil to effectively dry after the application of heat is based on the square of the cable diameter, and may be found using Equation (1). This equation says that if a cable (or other cylindrical heat source) of diameter d_1 has an effective drying time of t_1, another cable of diameter d_2 will exhibit an effective drying time of t_2, assuming the heat rate in the heat source is the same in both cases.

$$t_2 = t_1\left(\frac{d_2}{d_1}\right)^2 \tag{1}$$

Previous experiments have suggested that Equation (1) is not an effective predictor of the effective drying time of soil [3][4]. However, an equation relating drying times may exist whose form is different than given in Equation (1).

An experiment was performed as a confirmation experiment

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for results formerly determined showing that soil drying time did not follow Equation (1), and to try to discover if there is any relationship between cable diameter and the time it takes soil around a cable to dry. This paper describes the experimental methodology, gives the results of the experiment, and describes the statistical analysis and conclusions reached from that experiment.

III. DESIGN OF THE EXPERIMENT

Four cylindrical thermal probes of equal length and four different diameters were prepared similar to the requirements for the laboratory probes given in IEEE Std. 442 [5]. The diameters of the heat probes were 3.1mm, 6.7mm, 9.5mm and 15.9mm. The probes were designed so that their heat output can be controlled by controlling electrical current input. Each probe contained a thermocouple to measure the temperature of the probe exterior.

A sand sample was brought to a homogeneous moisture content of approximately 10% and then divided into twenty identical samples which were placed into twenty identical polyvinyl chloride (pvc) cylinders and sealed to prevent moisture loss. The cylinders were randomly divided into groups of four, and each cylinder had a probe size randomly assigned to it. Each of the samples were tested in random order. One set of 4 samples was tested each day.

The resulting experimental design is a single factor (the probe diameter) four level (3.1mm, 6.7mm, 9.5mm and 15.9mm) test with five replicates and a total of twenty samples. The day of testing was used as a blocking variable to remove any unwanted effects of testing the samples on different days.

Each sample was tested by placing the probe assigned to it into the center of the soil and connecting the probe to a source of electricity to inject current into the probe resulting in a measurable heating rate. Each sample was tested at approximately 0.44 W/cm for 45 minutes. The samples were weighed immediately before and after the testing to determine water loss, and the temperatures of the probes were measured continuously during the 45 minute test period. The response variables that were measured were the effective drying time as defined in references [1] and [2] and the total amount of moisture that was evaporated from each sample during the testing interval. Fig. 1 shows the temperature data gathered during a typical test.

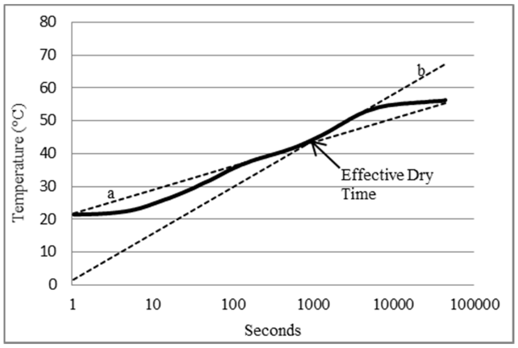

Fig. 1: Sample test showing effective drying time.

After the initial heating time the graph will attain a slope shown as "a" in Fig. 1. This is the slope from which the moist soil thermal resistivity can be calculated [5]. After continued heating the slope of the graph will abruptly change and exhibits a steeper slope, slope "b" in Fig. 1. A second soil thermal resistivity can be calculated from slope "b". This time at which the abrupt change between resistivity "a" and resistivity "b" occurs is defined as the "effective drying time".

In the case of a cable buried in soil, if the heat from the cable dries the soil to the point where the resistivity abruptly changes in this manner, the temperature of the cable will quickly increase since the resistance of the thermal circuit surrounding the cable has increased. The result could be cable failure due to overheating. The experiment was designed to determine if the diameter of the heat sources affects this effective drying time.

IV. EXPERIMENTAL RESULTS

The measured values for each probe in the order of testing are shown in Table I. The moist resistivity is the value calculated from slope "a" measured before the effective dry time and the dry resistivity is the value calculated from slope "b" after the effective time to dry.

Table I
Measured data in order of testing.

Test Order	*Probe Size (mm)*	*Effective Drying Time (sec)*	*Water Loss (g)*	*Moist Resistivity (cm°C/W)*	*Dry Resistivity (cm°C/W)*
1	9.5	717	0.9	57	164
2	6.7	735	0.8	79	160
3	15.9	762	0.9	93	182
4	3.1	563	0.6	93	160
5	9.5	744	0.5	57	163
6	3.1	703	0.6	81	186
7	15.9	779	0.6	99	179
8	6.7	797	0.6	93	182
9	15.9	972	0.7	128	172
10	3.1	731	0.6	81	172
11	9.5	818	0.7	66	183
12	6.7	824	0.7	100	200
13	15.9	1050	0.6	134	206
14	6.7	810	0.5	93	193
15	3.1	681	0.6	81	199
16	9.5	855	0.6	79	160
17	6.7	713	0.6	85	158
18	3.1	682	0.7	78	191
19	15.9	881	0.7	137	167
20	9.5	747	0.6	60	161

Table II and Table III arrange the effective drying time and total moisture loss measurements showing the measurements and average of the measurements for each probe size.

Table II
Effective drying time in seconds for each replicate by probe size.

Probe Size (mm)	*Observation Number*					
	1	*2*	*3*	*4*	*5*	*Mean*
3.1	563	703	731	681	682	672
6.7	735	797	824	810	713	776
9.5	717	744	818	855	747	776
15.9	762	779	972	1050	881	889

Table III
Total moisture loss in grams for each replicate by probe size.

Probe Size (mm)	***Observation Number***					
	1	***2***	***3***	***4***	***5***	***Mean***
3.1	0.6	0.6	0.6	0.6	0.7	0.62
6.7	0.8	0.6	0.7	0.5	0.6	0.64
9.5	0.9	0.5	0.7	0.6	0.6	0.66
15.9	0.9	0.6	0.7	0.6	0.7	0.70

V. ANALYSIS OF RESULTS

An analysis of variance approach was used to determine the effect of the probe diameter. The null hypothesis, H_0, was that the probe diameter had no effect on the effective drying time or the amount of water loss. The alternative hypothesis, H_1, was that the probe diameter did have an effect on the effective drying time or the amount of water loss. Table IV contains the results of the analysis of variance for the effective drying time.

Table IV
Analysis of variance for the effective drying time.

Source of Variation	***Sum Of Squares***	***DF***	***Mean Square***	***F_o***	***F***	
Probe size	117,339	3	39,113	13.45	3.49	
Blocking Factor	65,735	4	16,434	5.65	3.26	
Error	34,892	12	2,908			
Total	217,966	19				
Tukey Test						
$T_{0.05}$=	probe 1-2	probe 1-3	probe 1-4	probe 2-3	probe 2-4	probe 3-4
6.27	103.8	103.8	216.5	0.024	112.7	112.7

The statistical comparison that should be made is the comparison of the F_0 and F values from Table IV. F_0 is the F statistic computed from the data, and the F value is the F distribution value for the appropriate numbers of degrees of freedom (DF) to a 95% significance level [6]. If $F_0>F$ that means the value tested is significant and H_0 should be rejected and H_1 accepted. If $F_0<F$ then to a 95% significance level the null hypothesis H_0 cannot be rejected.

From Table IV, since $13.45>3.49$, the null hypothesis must be rejected—meaning at least one probe size did have an effect on the effective drying time. A Tukey test was used to compare the probe diameters to determine which of them did have an effect on the effective drying time. The probes are numbered one through 4 by ascending diameter. In the Tukey test, if the computed value for the probe pair exceeded the test value $T_{0.05}$, there would be evidence that the probe diameter change between the pair did have an effect on the effective drying time to a 95% significance level.

The results of the analysis show that each of the probes' diameters did have an effect on the effective drying time, except for the change between probes 2 to 3—the change between 6.7mm and 9.5mm. So, the results of the experiment resulted in the rejection of H_0 and acceptance of H_1. Probe diameter did have an effect on the effective drying time.

An analysis of variance was also done on the amount of water lost. The results are shown in Table V.

Table V
Analysis of variance for water loss.

Source of Variation	***Sum of Squares***	***DF***	***Mean Square***	***F_o***	***F***
Probe size	0.0175	3	0.005833	0.933	3.49
Blocking factor	0.137	4	0.03425	5.48	3.26
Error	0.075	12	0.00625		
Total	0.2295	19			

Analyzing Table V, since $0.933<3.49$ the null hypothesis cannot be rejected at the 95% significance level. There is no reason to reject the null hypothesis that the probe diameter did not have an effect on the amount of water lost by the soil during testing.

Since there is evidence that the probe diameter affects the effective drying time, but does not affect the total moisture loss, it appears that these are two different phenomena. One reason for this may be that as the diameter of the heat source gets larger, there is more water in contact with the probe. So, each water molecule is influenced by a smaller amount of heat energy as the probe diameter increases. The result is a reduction in the speed at which water vaporizes and migrates away from the source. The total amount of moisture that evaporates from the sample is influenced only by the amount of total heat available. This is a function of the current input to the probe and not affected by the probe diameter. A scatter diagram of the water lost plotted against the diameter of the heat source is shown in Fig. 2.

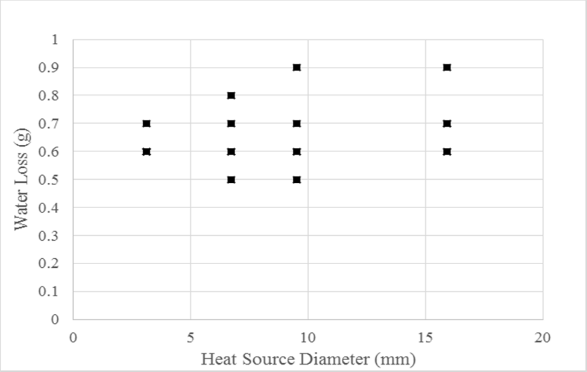

Fig. 2. Water lost vs heat source diameter.

Water vaporizes and migrates away from the vicinity of the heat source at a decreasing rate as the source diameter grows larger, but condenses somewhere in the sample away from the source and does not leave the sample altogether. This dries the soil in the immediate vicinity of the source and increases the resistivity but does not reduce the moisture in the entire sample.

It is also of note that the dry resistivities measured in Table I are not the same as the resistivity of the sand at a zero moisture content. The sand thermal resistivity when completely dry is between 300-350 cm°C/W which is much higher than the dry resistivities measured after the effective drying time. It appears that the effective drying time occurs some time before the soil sample completely dries.

A least squares linear regression was done to the data in Table I to find an equation relating probe size to effective drying time. The equation that was found to give the best fit to the data was Equation (2). The scatter diagram of the data along with the line created by the regression equation is shown in Fig. 3.

$$y = 15.85x + 638.5 \tag{2}$$

Where
y = effective drying time (seconds)
x = heat source diameter (mm)

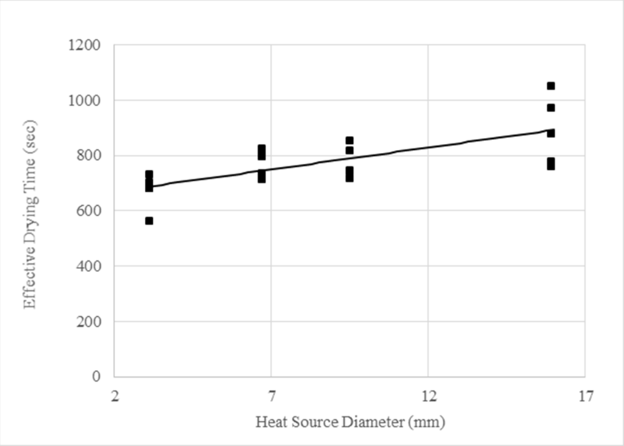

Fig. 3. Scatter diagram of effective drying time data and regression line.

The lack of fit statistic of the regression line created by Equation (2) was also computed. There was found to be no curvature to the regression line and there was no evidence of lack of fit of the regression line to the data.

VI. RESIDUAL ANALYSIS

The standardized residuals were computed and were plotted versus the predicted effective drying time in Fig. 4. The standardized residuals were also plotted against the order in which the tests were done in Fig. 5. A normal distribution plot was created and is shown in Fig. 6.

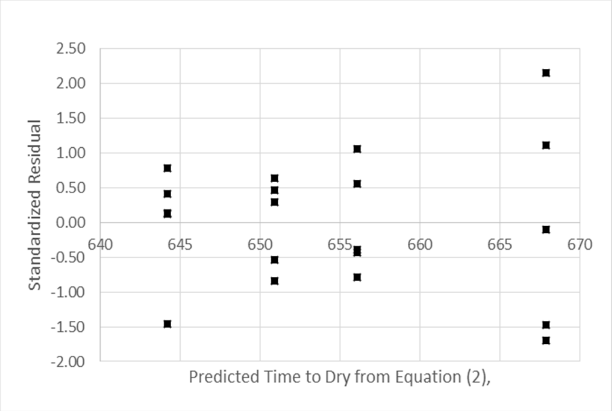

Fig. 4. Standardized residual plotted against predicted effective drying time from Equation (2).

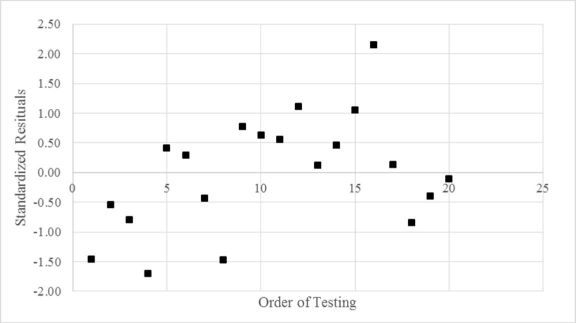

Fig. 5. Standardized residuals plotted against the order of testing.

None of the plots of the standardized residuals appears to show any problems with the measured data.

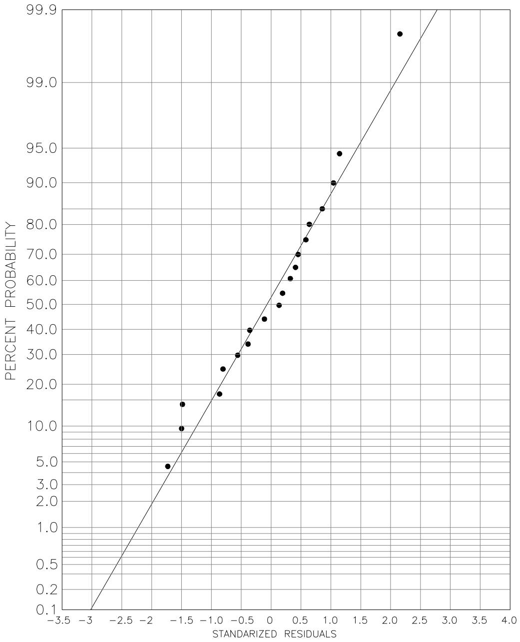

Fig. 6: Normal distribution plot of standardized residuals.

VII. CONCLUSIONS

The experiment reported herein shows that there is a relationship between the effective drying time and the diameter of the heat source. The relationship found, however, differs from that reported in some other sources. This confirms the results of past experiments. Rather than the effective drying time being related to the square of the diameter of the heat source by Equation (1), it appears that there is a simple first order relationship of the form in Equation (2).

In previous experimentation done by the authors there was found to be no effect of heat source diameter on the effective drying time [3][4]. This was probably due to the fact that the heat source sizes used in these past experiments were not sufficiently different in diameter for the effect of diameter on effective drying time to be clearly seen from the measured data. In the experiment reported in this paper the largest probe was five times larger than the smallest probe, allowing the relationship between diameter and effective drying time to be more easily seen. For example, in this experiment there appeared to be no difference in drying time between the 6.7mm and 9.5mm sources, which were the sources closest together in diameter. The differences in drying time between the 3.1mm and 15.9mm sources, however, could be clearly seen. If similar tests are done in the future to find equations relating source diameter to drying time it is important to use probes which differ in size by at least five times to make it possible to measure the effect of diameter on the drying time.

The experiment also showed that the effective time to dry is not the same as the time it takes to reduce the soil sample to 0% moisture content and the soil resistivity measured at the effective drying time is not the same as the soil resistivity at 0% moisture. The time necessary to reduce a soil sample to 0% moisture content will be much longer than the effective drying time. Therefore, in the effort to determine the soil thermal stability in the laboratory, the value that must be measured is effective drying time. If the value measured by the laboratory is the time to reduce a sample to 0% moisture content, and this is the time reported to the engineer designing the underground cables, the reported time will be much longer than the one needed for determining the actual soil thermal stability. The result will be a non-conservative underground cable design. The soil will be much less thermally stable than the reported drying times would appear to indicate. It is important to understand that the effective drying time is the value determining thermal stability and not the time to reduce the soil to 0% moisture content. Furthermore, only the effective drying time is affected by the cable diameter. The time it takes to reduce soil to 0% moisture content is unaffected by cable diameter. If an equation similar to Equation (2) is used to determine the expected soil drying time based upon soil drying time measured using a heat source of known diameter, the value that must be used is the effective drying time.

While experimentation confirms that the use of Equation (1) must be abandoned in characterizing the thermal stability of soil, laboratory tests determining effective drying time might still be useful. Equation (2) was derived for a single type of soil (sand) and would not be expected to hold true for any other type of soil. To determine the effect of source diameter on any particular soil of interest, a sample of that soil must be collected. It may then be tested in the laboratory to determine the effective drying time using two differing thermal source sizes. An equation similar to Equation (2) could be derived that would relate the effective drying time for the laboratory probe diameter to the diameter of cable to be installed. The question would still remain as to the propriety of extrapolating the results of this equation beyond the probe sizes used in testing. Furthermore, the uncertainty in relating the effective drying time to the actual effects of the soil thermal stability on the heating of an underground cable, will still remain. In other words, the relation of laboratory testing to *in situ* cable performance has not been adequately determined.

VIII. REFERENCES

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IX. BIOGRAPHIES

Keith Malmedal (M’91–SM’13) received his BSEET degree from Metropolitan State College of Denver in 1995, MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO.

He has over 24 years combined experience in electrical power system design and system study, teaching, and research, and is presently the President of NEI Electric Power Engineering, Arvada, Colorado, a consulting firm specializing in all aspects of power system engineering and design. He has published over 25 technical papers and taught university courses and short courses related to power systems, machines, protection, renewable energy, and energy policy issues.

Dr. Malmedal is also a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 18 states, and Alberta, British Columbia, and Ontario, Canada.

Carson Bates (M’09) received the B.S. degree in engineering with electrical specialty Magna Cum Laude in 2010, and the M.S. in electrical engineering in 2013 both from the Colorado School of Mines, Golden, CO.

He worked as an intern while pursuing his B.S. degree at the National Renewable Energy Laboratory in the Advanced Power Electronics for Vehicles group. His work primarily involved investigating heat transfer through an IGBT package. He currently works as a full time engineer at NEI Electric Power Engineering, which he has been doing since 2010. While employed there, he has had the opportunity to design multiple substations and industrial facilities. He has also spent significant time troubleshooting problems in existing facilities and inspecting construction activities.

David Cain received his Associates of Applied Science degree with two Certificates of Completion from the Community College of Aurora concurrent with his graduation from high school in 2011. Currently David is attending the Metropolitan State University of Denver majoring in Electrical Engineering Technology and expects to graduate with a BSEET by 2016.

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