

Effect of Moisture on Electrical Response of Sand and Clay under High Impulse Voltage Applications

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ABSTRACT

Soil plays an important role in ground designing. Engineers normally consider only soil resistivity under normal or steady state condition when designing the grounding system. Under certain circumstances such as lightning, electrical response of the soil will change accordingly and thus, the performance of the grounding system will be affected. The purpose of this study is to investigate the effect of moisture content on the electrical behaviour of sand and clay under high impulse voltage condition. Both soil samples are dried in the oven at $110 \pm 5^\circ\text{C}$ to remove the water content until became 0%. The samples are subjected to 30 shots of standard (1.2/50 μs) lightning impulse voltage for both positive and negative impulse polarities. This is followed by moistening the samples with 5% amount of water over the volume of the samples. The corresponding V50% for both sand and clay was calculated and the value obtained was converted to standard atmospheric condition. The voltage at breakdown and time to breakdown for each soil sample was analysed a statistical analysis conducted for these two parameters to determine if type of soil and moisture content have an effect on the breakdown voltage. In general, it was found that clay is more efficient in neutralising high impulse voltage than sand likely due to the former's low resistivity and porosity.

Keywords: Breakdown voltage, soil, electrical grounding, sand, clay

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INTRODUCTION

The study of electrical properties of soil yields invaluable information for research fields which include agriculture, geophysics and electrical grounding system (Lim et al., 2012, 2013a). In any electrical installation systems, it is pivotal to have an efficient grounding system. The performance of grounding system

is highly dependent on soil characteristic which is predominantly determined by the soil resistivity (Lim et al., 2013b, 2014). Yet, under transient and high voltage condition which is typically produced by lightning, the soil characteristic is significantly different from its static or steady state behaviour (Nor & Griffith, 2006). One way to characterise soil behaviour under high impulse voltage condition is by analysing its 50% breakdown voltage or $V_{50\%}$. This parameter can be used to gauge the ability of soil in discharging high impulse voltage. Soil with lower $V_{50\%}$ is expected to be more conductive within that transient period and vice versa. In addition, two more interesting parameters which can be analysed is the time to breakdown (*TBD*) and voltage at breakdown (*VABD*) of the soil sample (Lim et al., 2015).

Studies of similar nature have examined the response of soil under high impulse voltage condition (Nor & Griffith, 2006; Asimakopoulou et al., 2009). However, there is limited dearth of studies employing the statistical approach especially based on the two said parameters with the most recent one in (Lim et al., 2015). Moisture affects soil resistivity. Yet, the effect of moisture content (MC) in clay and sand on its response to high impulse voltage shot is not discussed extensively in the literature. Most of the past studies have focused on sand (Nor & Ramli, 2003; Cabera et al., 1993). Recent studies have looked at sand and clay. Clay is studied due to the fact that its physical properties are opposite to sand especially in terms of resistivity and porosity (Joffe & Lock, 2010). In addition, clay alongside with sand is also highly researched in terms of its steady state, low frequency resistivity behaviour but rarely in high frequency high voltage condition. Therefore, the primary objective of this research is to analyse and compare the electrical behaviour of both sand and clay in terms of $V_{50\%}$, *TBD* and *VABD* under high impulse voltage condition since sand and clay have contrasting values in terms of soil resistivity (Markiewicz & Klain, 2003). Results provide better understanding on the electrical behaviour of sand and clay under high impulse voltage condition in which the findings are useful for future researchers interested in electrical properties of soil. Protection engineers may also find these findings useful as protective relays may be affected by electrical responses of soil under both static and high voltage transient conditions.

METHODOLOGY

This research project is outlined in Figure 1. Two types of soil samples were used, namely sand and clay. The sand was filtered and sieved to remove the pebbles in order to get pure coarse sand. As for the clay, it was crushed into powder form and then compacted. Both samples were dried in the oven for approximately 16 hours at the temperature of 110 ± 5 °C using a metal container in order to have practically 0% MC (Department of Transportation, 2003). This is to produce soil without MC. Then, 5% water by mass was introduced to these completely dried soil samples before being uniformly mixed in the cylindrical acrylic container. This step is to produce soil with 5% MC. The temperature and relative humidity are measured and recorded at the beginning of the experiment as these parameters are required to convert the experimental values to its equivalent values at standard reference atmospheric condition. This is discussed in the next section.

Each of the soil sample prepared was then subjected to up and down analysis to determine the breakdown voltage for both positive and negative impulse polarities (Lim et al., 2015). The experiment was done for samples with 0% MC followed by samples with 5% of MC. The design setup as shown in Figure 2 consists of a cylindrical acrylic container with inner diameter of 242mm and height of 105mm with the copper rod having an approximate dimension of 15mm diameter and 300mm height. The acrylic container is filled with the samples up to a fixed 65mm for both types of soil. A cylindrical metal plate with diameter of 240mm and thickness of 5mm is placed inside and at the bottom of the acrylic container to guide the impulse current through the soil sample as well as to channel the impulse current directly to the ground through a ground wire whenever there is a breakdown detected through the waveform displayed at the oscilloscope.

The impulse voltage was generated using a 3-stage Marx Generator having the capability of producing standard high impulse voltage ($1.2/50\mu s$) as per IEC standards. For the purpose of this experiment, the generator was configured to operate in two stages with a range of 0V to 130kV per stage of configuration. Each sample is subjected to 30 shots of impulse voltage with fixed 90-second interval between each shot for both polarities to ensure that the soil has regained its initial properties before the next shot is applied. The impulse voltage signal was captured on a DSO09104A Agilent Infinium 9000 Series Oscilloscope which has the specifications of 1GHz, 4 channels and the analog sampling rate of 5GSa/s.

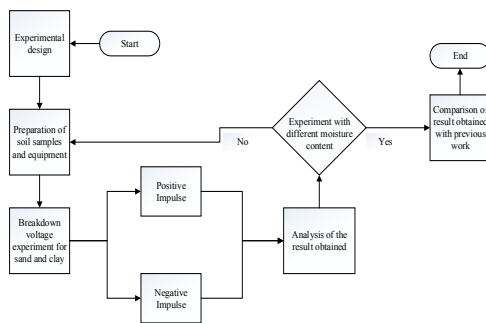


Figure 1. Research flow

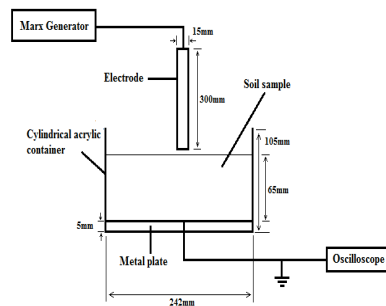


Figure 2. Setup of the experiment

Initially, the soil sample was subjected to random impulse voltage in order to determine the minimum breakdown voltage of the sample, V_0 . Up and down analysis was used in this experiment for both positive and negative impulse polarities in which after V_0 was obtained, it was then followed by stepping up whenever there was breakdown and stepping down whenever there was no breakdown with a step voltage of 2kV. The result from Up and Down analysis was used to calculate the $V_{50\%}$ and standard deviation (SD) of each soil sample using the formula (Campos, 1995). The results of the $VABD$ and TBD were analysed statistically using the independent samples T-test method in the SPSS software. Independent samples T-test compares the means of two unrelated groups and evaluates them. This test will indicate

whether the sand and clay is significantly different from each other by comparing the means between sand and clay soil sample in terms of $VABD$ and TBD .

RESULTS AND DISCUSSIONS

Table 1 depicts the breakdown voltage ($V_{50\%}$) for both positive and negative impulse polarities with 0% and 5% MC. The values shown are the values which have been converted to their corresponding breakdown voltage values under standard atmospheric condition by following the procedures recommended by Hauschild and Lemke (2004) where temperature, $T_0 = 20^\circ\text{C}$ (293 K), absolute air pressure, $P_0 = 1,013$ hPa (1,013 mbar) and absolute humidity, $h_0 = 11$ g/m³. It is clear that the $V_{50\%}$ for positive impulse is higher than the negative impulse and sand has higher breakdown voltage for both polarities compared with clay given the same amount of MC. This implies that clay is more efficient in discharging high impulse voltage compared with sand.

Table 1
Breakdown voltage of sand and clay at standard condition

Applied Voltage	MC (%)	Sample A (Sand)		Sample B (Clay)	
		$V_{50\%}$ (kV)	SD (kV)	$V_{50\%}$ (kV)	SD(kV)
Positive impulse	0	61.2	4.9	46.2	4.2
	5	35.6	2.9	34.4	4.8
Negative impulse	0	50.7	4.7	41.2	2.6
	5	34.2	2.9	32.3	2.5

The comparisons between the voltage traces for both no breakdown and breakdown voltage are shown in Figures. 3, 5, 7 and 9 for positive impulse and Figures 4, 6, 8 and 10 for negative impulse. Whenever breakdown occurs, a sudden collapse of voltage appears which indicates that the soil sample becoming conductive at that particular instant of time where the impulse current can pass through the soil and directly discharge through the grounding wire. It is also observed that the $V_{50\%}$ for positive polarity is higher than negative polarity for all the voltage traces (Figure 3 – Figure 10). Meanwhile, the voltage traces show reduction in $V_{50\%}$ between sand 0% and sand 5% (Figure 3 – Figure 6) for both polarities. The same result can be observed for clay 0% and clay 5% (Figure 7 – Figure 10). The reduction in the $V_{50\%}$ is due to the effect of moisture added to the soil sample which has caused the soil resistivity to decrease, thus increasing the tendency for the soil sample to be more conductive. When a comparison is done between sand and clay for both 0% (Figures 3, 4, 7, 8) and 5% (Figures 5, 6, 9, 10) MC for both polarities, it is found that sand has higher $V_{50\%}$ than clay. This is referring to the fact that the soil resistivity in sand is higher than clay (Markiewicz & Klain, 2003). Note that the above mentioned are based on physical observation. The following provides a statistical analysis.

When 5% amount of moisture is added to the sample, the sand and clay experience lower $V_{50\%}$ in which the efficiency of discharging the impulse voltage is higher than 0% MC. This is possibly due to some of the energy from the impulse voltage are being absorbed by the

water. It is found that there is a gap between no-breakdown and breakdown voltage as shown in Figures. 5, 6, 9 and 10. The reason why the gap for sand is bigger than clay is probably due to the porosity level of clay which is higher than sand. This means that clay particles absorb more water than sand particles, thus, the amount of water left to fill the void (outside the clay particle) between the clay particle is lesser than sand (Joff & Locke, 2010). Energy absorption by water in clay is less than the energy absorption by water in sand. In addition, the presence of moisture has caused a higher amount of reduction of $V_{50\%}$ in sand than clay under both polarities. A possible explanation is again due to the porosity of sand which retains more moisture. Therefore, a significant portion of the impulse current will flow through the moisture in sand.

Positive Impulse

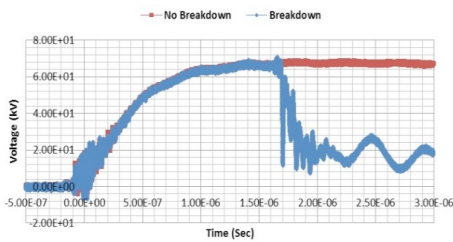


Figure 3. Sand 0% moisture

Negative Impulse

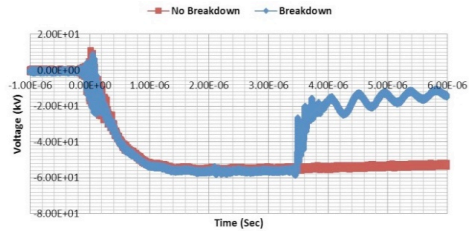


Figure 4. Sand 0% moisture

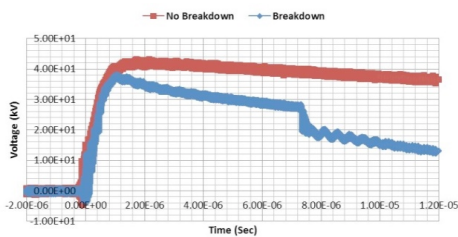


Figure 5. Sand 5% moisture

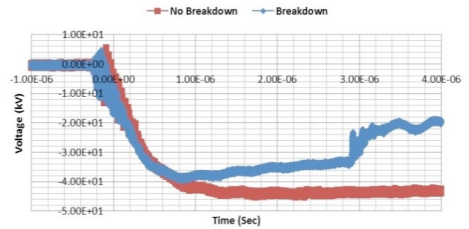


Figure 6. Sand 5% moisture

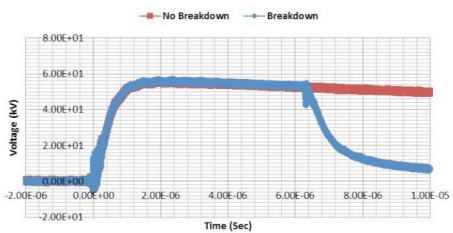


Figure 7. Clay 0% moisture

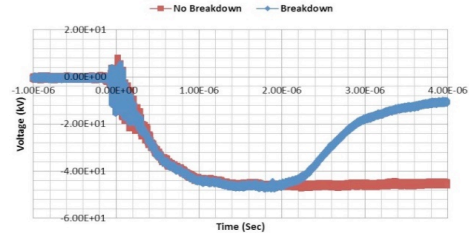


Figure 8. Clay 0% moisture

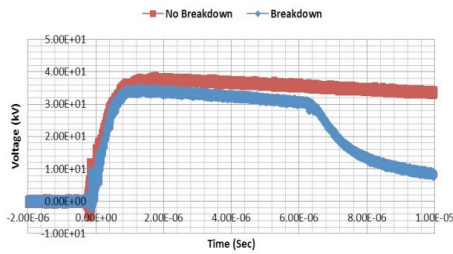


Figure 9. Clay 5% moisture

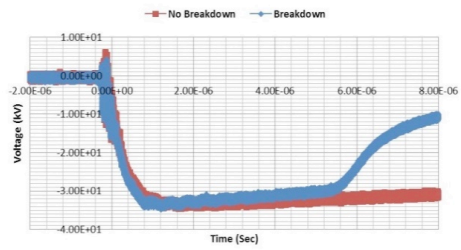


Figure 10. Clay 5% moisture

In sand 0% for both impulse polarities, the voltage profile experiences fluctuation before it reaches stable state upon completion of dampening of the oscillations. The density of oscillation decreases as the sand is moistened. This oscillation is probably due to the breakdown of the small air particles present between the sand particles before it reaches the metal plate connected to the ground wire. When 5% of moisture is added to the sand, the water particles replace the air to fill in the void. Based on Jin et al. (2001), the breakdown voltage of water is five times smaller compared with air in which it can be seen clearly in the graph that oscillation for sand 5% is much smaller than sand 0%. In clay 0% and 5%, there are no traces of oscillation in the breakdown graph. This is due to the particle size of clay (<0.002mm) which is 25 times smaller compared with sand (0.05 mm to 2mm) that caused clay having less air gap to be filled by air (Whitlow, 2004). This could explain why clay does not have any oscillation after the breakdown.

Another two parameters which can be analysed other than $V_{50\%}$ are $VABD$ and TBD . The difference between $VABD$ and $V_{50\%}$ breakdown voltage is that $VABD$ is the potential arise across the soil sample at breakdown event and $V_{50\%}$ is the voltage at which there is 50% probability of the sample experiencing electrical breakdown. The average values for $VABD$ and TBD from the up and down analysis method are depicted in Table 2 for positive impulse and Table 3 for negative impulse respectively. One interesting observation that can be found is that, the average TBD is always lower with higher amount of MC. In other word, the average TBD for sand 0% is lower compared with sand 5% for both impulse polarities. Similar results can be seen with clay 0% and clay 5% for both impulse polarities. This is probably due to the average TBD for air being lower than water. Further research needs to be done to support this hypothesis.

Table 2
Positive impulse voltage at breakdown and time to breakdown

Samples	Average $VABD$ (kV)	SD (kV)	Average TBD (μ s)	SD (μ s)	Lag / Lead
Sand 0%	61.13	2.53	1.48	0.22	Lag
Sand 5%	36.75	1.91	3.67	1.26	Lag
Clay 0%	46.27	1.98	3.65	2.09	Lag
Clay 5%	35.38	2.5	3.95	2.06	Lag

Table 3
Negative impulse voltage at breakdown and time to breakdown

Samples	Average <i>VABD</i> (kV)	SD (kV)	Average <i>TBD</i> (μ s)	SD(μ s)	Lag / Lead
Sand 0%	51.33	2.23	1.79	0.62	Lag
Sand 5%	35.13	1.93	3.58	1.35	Lag
Clay 0%	42.27	1.67	1.49	0.3	Lag
Clay 5%	33.25	1.77	5.39	2.25	Lag

Standard deviation is used to quantify the distribution of *VABD* and *TBD*. Based on Table 2, there is no trend in the standard deviation for both average *VABD* and *TBD*. Hence, more experiments at different *MC* levels are needed for any solid conclusion to be drawn with regards to the effects of the types of soil on the standard deviation values. It is also found that, the average *TBD* for all the soil samples are under the ‘lag’ behaviour which is defined as the *TBD* of soil sample being exceeded the standard 1.2μ s rise time of impulse voltage. On the other hand, when the *TBD* is less than 1.2μ s, it is considered as lead behaviour. The result of *TBD* for sand 0% positive impulse with its respective standard deviation is approximately the same with the result obtained in (Lim et al., 2015).

These two parameters were further analysed statistically using the Independent T-test to verify whether there are any significant differences between the two types of soil samples. Interestingly, a statistical analysis on *TBD* and *VABD* was rarely captured in earlier studies on this high voltage experimental research field. An exception is Lim et al. (2015) where a statistical analysis was conducted on different types of grounding backfill materials under high impulse voltage condition. The independent T-test was performed for two categories, namely positive impulse and negative impulse. The two test sample combinations are the same for both positive and negative impulse polarities and for the following; Sand 0% - Sand 5%, Sand 0% - Clay 0%, Clay 0% - Clay 5%, and Clay 5% - Sand 5%. The confidence level was set at 95% which means that if the computed P value is less than 0.05, then there is statistical significant difference between the compared test samples. Table 4 and Table 5 show the Independent T-test results for both impulse polarities.

Table 4
Positive impulse voltage independent sample t-test

Sample for Independent T-test	P-value of <i>VABD</i>	Significant Difference	P-value of <i>TBD</i>	Significant Difference
Sand 0% - Sand 5%	0.000	Yes	0.000	Yes
Sand 0% - Clay 0%	0.000	Yes	0.000	Yes
Clay 0% - Clay 5%	0.000	Yes	0.690	No
Clay 5% - Sand 5%	0.091	No	0.638	No

Table 5
Negative impulse voltage independent sample t-test

Sample for Independent T-test	P-value of <i>VABD</i>	Significant Difference	P-value of <i>TBD</i>	Significant Difference
Sand 0% - Sand 5%	0.000	Yes	0.000	Yes
Sand 0% - Clay 0%	0.000	Yes	0.107	No
Clay 0% - Clay 5%	0.000	Yes	0.000	Yes
Clay 5% - Sand 5%	0.008	Yes	0.012	Yes

It can be inferred from Table 4 and Table 5 that there are statistically significant differences for sand 0% and sand 5% for both polarities. This suggests that the moisture added to the soil sample does have an effect on both *VABD* and *TBD* for these two samples. As for clay 0% and clay 5%, it is found that the moisture only has an effect for both *VABD* and *TBD* for negative polarity. Meanwhile, for comparison between sand and clay soil samples, it is found that, the moisture does have an effect for *VABD* for both 0% and 5% MC at both polarities. As for the *TBD*, the moisture only has an effect for the combination of sand 0% - clay 0% for positive impulse and clay 5% - sand 5% for negative impulse.

CONCLUSION

In conclusion, sand has a higher breakdown voltage compared with clay for both impulse polarities and the breakdown voltage for positive impulse polarities is higher than the voltage for negative impulse polarities for both type of soil with 0% and 5% MC. When 5% of moisture was added to both soil samples, the graph of the breakdown voltage is lowered from the no-breakdown graph. Upon analysing the traces of the breakdown voltage, it can be seen clearly that right after the breakdown event, the voltage waveform for sand 0% is oscillatory and as 5% moisture is added, the oscillation is reduced. As for the clay, there is no oscillation after the breakdown. This suggests that the particle size of soil has an effect on the trend of the breakdown voltage traces. The aforementioned experiments can be replicated by considering variation of grain size and compaction level of soil. It is also worth to further investigate the oscillatory response in the breakdown phenomena of soil. Findings from this experiment may provide useful insights for other research fields as well as agriculture and geophysics especially in countries which have lightning prone areas. It would also be interesting to extend this study to find out whether there is any effect of such electrical response of soil to the tripping operation of protective relays.

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