1. Introduction

Earthing (or Grounding) installations are evidently one of the most misunderstood, undervalued and neglected electrical component despite its imperative role in the electricity distribution system. *Earthing* installations are often neglected because of the natural tendency to overlook things that are not visible (i.e. since these are installed underground). Another reason is due to the lack of adequate understanding and awareness of *Earthing* systems. It is also very difficult for the authorities to inspect and monitor the thousands of *Earthing* installations. Irrespectively, *Earthing* is an electrical installation designed to safely divert any unintentional hazardous currents/voltages into the *earth*/ground. It must also provide a common reference voltage point in an electrical circuit/system. Because it plays a vital role, it is a mandatory installation by regulation for all houses, power, telecom, IT systems, other facilities, etc. An *Earthing* installation has the following three main functions:

(i) *Safety of lives* - Electrical faults occur occasionally and even small fault/leakage currents can be hazardous (and even fatal). *Earthing* installations must maintain the Step and Touch voltages within safe limits.

(ii) *Protection of facilities, houses, machines and equipment* - A good *Earthing* installation is essential for fixing the reference voltage at 0V (or very close to 0 V at all times). Electrical/electronic protection devices will not function properly without proper *Earthing* and hazards (including fire) may occur. Without reliable *Earthing* installations, MCBs will not operate during *earth* faults, Lightning Arrestors and Surge Arrestors will not function effectively against lightning and switching surges.

(iii) *Proper operation of electrical, telecommunication, and IT equipment*- All electrical equipment need to be properly *earthed* for proper operations. (E.g. With an ineffective *Earthing*, a distribution transformer neutral voltage will not be fixed at 0V (but will fluctuate with unbalanced loads) and will subject consumer loads to large voltage variations (especially during faults). Consequently, consumer electronics can malfunction or can be damaged or life shortened. Proper earthing is also essential to minimize system crashes/hang-ups and data corruptions in computer communication electronics to function efficiently. Ground loops due to faulty *earth* connections are a primary cause).

This paper is written in the context of Bhutan and the neighbouring Himalayan region where it is usually difficult to achieve low resistance *Earthing* installation on a sustained basis due to the unfavourable soil conditions (i.e. high soil resistivity). Unlike the low lying vast fertile plains defining the terrain of many countries around the world, driving one or two *Earthing* rods into the ground will seldom provide adequately low *Earth* resistance. Further, even if adequately low *Earth* resistance is achieved with some new installations, the real performance test lies in whether the installation provides a consistently low and stable *Earthing* resistance throughout the year and also in the durability of such installations. While most conventional *Earthing* installations provide greatly fluctuating resistances, the conventional salt based installations deteriorate rapidly too. There is therefore an urgent need to establish (with facts rather than with opinions), to explain and compare objectively the various common *Earthing* technologies to enable well informed selection of the best *Earthing* technology by users. This paper is particularly written to provide a better understanding of the common *Earthing* technologies and an objective comparison of the various options.

2. *Earthing* technologies used in Bhutan (and neighbouring regions)

The conventional salt-charcoal based pipe or plate *Earthing* is evidently the most widely used *Earthing* technology in the electricity distribution sector (including house *Earthing*) in Bhutan. Because salt-charcoal *Earthing* is neither reliable nor durable, many houses and facilities have resorted to *Earthing* rods and *Earthing* strips. Similarly for the same reasons, in the recent times Druk-Care Engineering's new *Earthing* technology (i.e. Ground & Electrode Enhancement (GEE) slab *Earthing*) has been gaining popularity. All these options can be explained scientifically and also through calculations which enable the pros and cons to be seen for what they are (rather than through just random opinions and speculations of the people in the industry). The following sections provide an objective evaluation of each of the common *Earthing* technology used in the country.

2.1 Conventional salt-charcoal based pipe and plate Earthing installations

A salt-charcoal based pipe electrode *Earthing* installation basically involves digging a pit of around 9 ft deep into which a pipe electrode (usually 2.5 m long and 4 cm diameter) is centered and the pit backfilled with salt, charcoal and soil (and compacted in tandem). The same process is followed for installing salt-charcoal based plate electrode but the pit need not be as deep. The purpose of salt is to form an electrolyte when water is poured into the pit (this greatly lowers the soil resistivity). The purpose of charcoal is to help in retaining moisture and also to enhance the soil conductivity (due to its high carbon content). While the operational principles are well intended, it is now well known that the actual performance of such *Earthing* installations is very deficient. Firstly, salt requires water to form an electrolyte and is therefore not effective in dry soil (especially during dry seasons). During wet seasons, salt dissolves in water (or even gets washed away in porous soils) and depletes completely over a short period of time. This explains why the *Earthing* resistances vary greatly between wet and dry seasons (even if water is poured regularly into the pit). Secondly, salt (NaCl) accelerates the corrosion of the electrode and the joint (i.e. electrode-conductor joint). Consequently the electrode and the joint deteriorate rapidly. In addition, the corrosion byproducts deposited on the electrode surface are electrically non conductive and greatly increase the *Earthing* resistance. Therefore, salt-charcoal based *Earthing* installations are neither reliable nor durable.

The field data (tabulated below) from the annual transformer *Earthing* inspection reports of erstwhile Central Maintenance & Training Division (CMTD), Beygana, BPC, also corroborates this point beyond any doubt. The national averages shown below may actually be even higher if the more remote (i.e. less accessible to vehicles) transformer stations were included in the samples.

Year	No. of transformers sampled across Bhutan	National average transformer *Earthing* resistance measured (Ohms)	Type of *Earthing* installation for each transformer station (according to prevailing standards)
2007	165	53	3 sets of salt-charcoal based pipe *Earthing* connected in parallel
2010	165	165	
2011	220	455	

Examples of defunct salt-charcoal based *Earthing* installations are shown in the pictures below. The *Earthing* electrode need not be as badly deteriorated as those shown in the pictures for the *Earthing* installations to be rendered non-functional. Such *Earthing* installations are hardly effective once corrosion byproducts start depositing on the electrode surface. One of the apparent reasons of why there are a multitude of defunct *Earthing* installations is because of the difficulty for electricity utilities to monitor thousands of *Earthing* installations. It is also evident that the *Earthing* conductor (usually bare and exposed) could be dangerously charged (due to faulty wiring, tampering, insulation deterioration, etc) when the *Earthing* installation is non-functional or defunct. Electrical hazards often occur for this very reason.

The corroded plate (left) is of copper. This shows that the common belief that copper electrodes will not corrode is not true.

Given the generally unfavourable *Earthing* soil conditions (i.e. high soil resistivity) of Bhutan, it is not difficult to understand the limitations of conventional salt-charcoal based pipe or plate *Earthing* even through theoretical calculations (based on commonly used standard formulas). The approximate achievable *Earthing* resistances for single pipe electrode and that of single plate electrodes for various soil resistivities are tabulated below in Table 1.

Table 1 : *Comparison of salt-charcoal based Earthing technologies (i.e. single pipe electrode and single plate electrode)*

Electrode type	Formula to calculate earthing resistance (Ohm)	Calculated Earthing resistance (Ohm)									
soil-resistivity (Ohm-m) ----------------------->		50 Ohm-m	100 Ohm-m	150 Ohm-m	200 Ohm-m	250 Ohm-m	300 Ohm-m	400 Ohm-m	500 Ohm-m	750 Ohm-m	1000 Ohm-m
Single Pipe	$R = \frac{\rho}{2.73L} \text{Log}_{10} \frac{4L}{d}$	18	35	53	70	88	105	141	176	264	351
Single Plate	$R = \frac{\rho}{A}\sqrt{\frac{\pi}{A}}$ Ohms	145	290	435	580	726	871	1161	1451	2176	2902

***Note*:**

(i) *The pipe electrode dimensions used in the calculation above are: Length=2.5m and Diameter=4cm*

(ii) *The plate electrode dimensions used in the calculation above are: Length=0.6m and Breadth=0.6m*

Given that the soil resistivity at *Earthing* sites around the country is generally high (greater than 1000 ohm-m at many sites), the difficulty of obtaining lower *Earthing* resistance using a pipe or a plate electrode is evident. It is also clear from above that pipe electrodes will provide a more effective *Earthing* installation compared to plate electrode (i.e. for the standard sizes assumed above). It is important to note that such *Earthing* installations usually provide substantially lower *Earthing* resistance initially. This is only possible because of the initial abundance of electrolyte (i.e. dissolved salt in water) which permeates the immediate surrounding soil to drastically lower the soil resistivity. However, as the salt depletes and as the electrode corrodes, the *Earthing* resistance increases greatly.

What would be the impact if we connect multiple pipe electrodes in a ring? An approximate estimate of the *Earthing* resistance can be obtained from the following formula.

$$R_R = \frac{\rho}{2\pi n \ell_r}\left(\ln\frac{294.3\,\ell_r}{d_r} + \frac{2\,\ell_r}{s} + \ln\frac{2n}{\pi}\right)$$

Source: US department of Agriculture, Rural Electrification Administration

Where: R_R = *Earthing* resistance (Ohms)
ϱ = soil resistivity (Ohm-m)
n = number of electrodes
l_r = electrode length (m)
d_r = electrode diameter (m)
s = Spacing between electrodes (m)

Using the formula above for multiple pipe electrodes connected in a ring, Table 2 below provides a comparative estimate of *Earthing* resistances obtainable by a double, triple, and quadruple pipe electrodes in various soil resistivity. The main point being made here is that given the generally high soil resistivity of Bhutan, even installing four pipe electrodes in parallel (in a ring) with an inter spacing of 6 m each, it is very difficult to obtained adequately low *Earthing* resistances on a sustained basis. It must be kept in view that the *Earthing* resistances could be low initially (when new) while the salt lasts and while the electrode has not corroded significantly.

Table 2 : ***Salt-charcoal based pipe Earthing (by number of pipe electrodes in parallel)***

Soil resistivity (Ohm-m)	Single pipe *earth* Resistance (ohms)	Double pipe *earth* Resistance (ohms)	Triple pipe *earth* Resistance (ohms)	Quadruple pipe *earth* Resistance (ohms)
50	18	10	7	6
100	35	20	14	11
150	53	30	21	17
200	70	40	28	22
250	88	50	36	28
300	105	60	43	33
400	141	80	57	45
500	176	100	71	56
750	264	150	107	83
1000	351	200	142	111

From the above facts and analysis, one would naturally wonder about the existing thousands of salt-charcoal based electrical earthing installations that would evidently be defunct (i.e. ineffective). Although the risks and impacts of such ineffective *Earthing* installations are substantial, the evaluation and analysis of the risks and impacts are beyond the scope of this paper (this will be addressed separately in another paper).

2.2 Earthing rods (spikes) driven into ground

Given the abundance of rocks in the ground in Bhutan, it is generally very difficult to drive even a 1.8 m stake (*Earthing* rod) into the ground (let alone the deep rod installations which are commonly done in other countries). Therefore if an *Earthing* rod is to be entirely buried vertically in the ground, installing *Earthing* rods would normally entail digging a pit, centering the *earth* rod and backfilling the pit with soil and compacting the soil in tandem. For calculating the *earth* resistance obtainable with a single, double, triple and quadruple *Earthing* rods the same formulae for pipe electrode above can be applied. Only the electrode length and diameter will need to be changed according to the *Earthing* rod specifications. But since the *Earthing* rods commonly used are smaller in size (i.e. normally around 1.8 - 2.5 m long and 2 cm in diameter), it is obvious that the calculations will yield higher *Earthing* resistances than that for pipe electrodes. It is therefore evident that *Earthing* rods will not provide adequately low *Earthing* resistance in the prevalent poor soil conditions of Bhutan (unless numerous *Earthing* rods are installed for every single *Earthing* point which may not be practicable due to greatly increased costs and work volume). It is therefore important to note here that the multitude of facilities relying on *Earthing* rods (even quadruple rods installations) most probably do not have adequate *Earthing* utility.

2.3 Pipes encased inside electrically conductive compounds

A few such *Earthing* installations utilizing pipes encased in electrically conductive compounds (such as those of conductive cement, moisture booster, etc) have also been installed in the country. Assuming that these compounds are indeed very conductive as claimed by suppliers, the same formulae for pipe *Earthing* used to derive the figures in Table 1 and Table 2 can be used with the electrode diameter increased to the diameter of the cylinder formed by the conductive material rammed around the pipe. Although, the diameter of the cylinder of conductive material formed is usually less than 25cm (otherwise huge quantity of conductive material will be required), a diameter of 30 cm has been assumed in Table 3 below to assess the potential of this option. Table 3 below provides a comparative estimate of *Earthing* resistances obtainable by a single, double, triple, and quadruple pipe electrodes (i.e. encased in conductive material) in various soil resistivity. The effective electrode diameter assumed to be 30 cm and the length is assumed to be 2.5m.

Table 3 : ***Pipe electrode encased in very conductive material (by number of pipe electrodes in parallel)***

Soil resistivity (Ohm-m)	Single pipe *earth* Resistance (ohms)	Double pipe *earth* Resistance (ohms)	Triple pipe *earth* Resistance (ohms)	Quadruple pipe *earth* Resistance (ohms)
50	11	7	5	4
100	22	14	10	8
150	34	20	15	12
200	45	27	20	16
250	56	34	25	20
300	67	41	30	24
400	89	54	40	32
500	112	68	50	40

750	167	102	75	59
1000	223	136	99	79

Encasing pipe/rod electrode with electrically conductive compound basically increases the effective diameter of the electrode. The extent by which *Earthing* resistance can be lowered by encasing pipe/rod electrode in conductive compounds such as "moisture booster" can be estimated by comparing the data in Table 3 and Table 2. While the reduction obtained is comparatively significant, it is clear that this option will not be cost effective (even where technically viable) as the soil resistivity increases over 200 ohm-m. This is not only because digging several 8-9 ft deep pits in rocky grounds is difficult and labour intensive, but also large quantities of the conductive material would be required for several installations. However, encasing pipe/rod inside conductive material (such as conductive concrete) will definitely provide a far more reliable and durable option as compared to salt-charcoal backfill. It may also be appropriate to mention here that using bentonite as the conductive compound to encase the pipe/rod has some problems. Bentonite clay works fine when wet (by expanding greatly when wet and pressing against the pipe/rod thereby lowering the electrode contact resistance). However, when dry it shrinks and pulls away from the pipe/rod thereby greatly increasing the electrode contact resistance. Using Bentonite clay will therefore result in huge variations in *Earthing* resistance.

2.4 Earthing strips buried horizontally in the ground

Another common form of *Earthing* (especially in the switchyards and substations) is the use of *Earthing* strips buried horizontally. Burying long *Earthing* conductors horizontally at about 0.6m deep below ground level actually provides a more cost effective *Earthing* than vertical pipe or rod electrode or plate electrode. An estimate of the obtainable *Earthing* resistance by a given length of *Earthing* strip conductor in a given soil resistivity is provided by the following formula.

$$R = \frac{100\rho}{2\pi l} \log_e \frac{2l^2}{w\ t} \text{ ohms}$$

Where,
ρ = soil resistivity (ohm-m)
l = length of strip (cm)
w = Burial depth (cm)
t = width of strip (cm)

Assuming standard 1 inch (i.e. 2.54cm) wide *Earthing* strips, the *Earthing* resistance estimates for various *Earthing* strip lengths and soil resistivity are calculated using the above formula and tabulated in Table 4 below.

Table 4 : ***Horizontal strip Earthing (by strip Earthing length)***

Soil resistivity (Ohm-m)		***Earthing* resistance (Ohm)**			
Conductor strip length (m) -------->		***5m***	***10m***	***15m***	***20m***
50 Ohm-m		13	8	5	4
100 Ohm-m		26	15	11	9
150 Ohm-m		38	22	16	13
200 Ohm-m		51	30	22	17

250 Ohm-m		64	37	27	21
300 Ohm-m		77	45	33	26
400 Ohm-m		102	60	43	34
500 Ohm-m		128	75	54	43
750 Ohm-m		191	112	81	64
1000 Ohm-m		255	150	108	86

From Table 4 above, it is evident that burying a long *Earthing* strip horizontally provides a more cost efficient means of *Earthing*. For instance, for the same soil resistivity, it is seen that just a 5 m horizontally buried *Earthing* strip will provide a lower *Earthing* resistance than a standard single pipe electrode. Similarly, a 15m horizontally buried *Earthing* strip will provide about the same *Earthing* resistance as that of quadruple pipe *Earthing* connected in a ring. Strip *Earthing* installations will especially be cost efficient where the top soil is of lower resistivity than the underlying soil. However, it is evident that for higher soil resistivities, strip *Earthing* will entail the installation of long *Earthing* strips (and this may not be practicable due to space constraints). Moreover since *Earthing* strips do not absorb moisture, the strip-soil contact resistance varies greatly with the soil moisture content. Consequently, *Earthing* strips do not provide a stable (i.e. reliable) *Earthing* resistance throughout the year.

2.5 Ground & Electrode Enhancement (GEE) slab Earthing

In order to overcome the problems (i.e. short life, poor reliability, need for regular monitoring and maintenance) associated with conventional *Earthing* installations (especially the salt based *Earthing*), GEE *Earthing* slabs were developed and fine tuned over several years. GEE slabs are composed of conductive particles and fibers, conductive meshes and GI flat encased in a predetermined proportion and orientation in concrete material. The alkalinity of concrete protects the metallic components from corrosion (just like concrete protects the encased steel bars in RCC buildings) and is therefore very durable. While the conductive matrix itself makes the GEE slab electrically very conductive, the hygroscopic slab also absorb moisture from surrounding soil further enhancing conductivity and lowering the *Earthing* resistance.

In addition, the large surface area in contact with the soil ensures higher conductance and also higher capacitance that lowers surge impedance (and therefore more effective in dissipating lightning surges, power switching impulses and transients). GEE *Earthing* slabs are prefabricated electrically conductive concrete slabs that are designed to be buried horizontally (at about 2 feet below ground level) and chain linked into various lengths according to the: site soil conditions; grounding application; and space availability. The following formula provides an estimate of the *Earthing* resistance obtainable for a given length (and installation depth) in a given soil resistivity.

$$R = K\frac{\rho}{2.73L}\ Log_{10}\frac{2L^2}{WD}$$

Where,
K = 0.5 to 1 (Coefficient)
ϱ = soil resistivity (ohm-m)
L = length of GEE slab *Earthing* (m)
W = width of GEE slab (m)

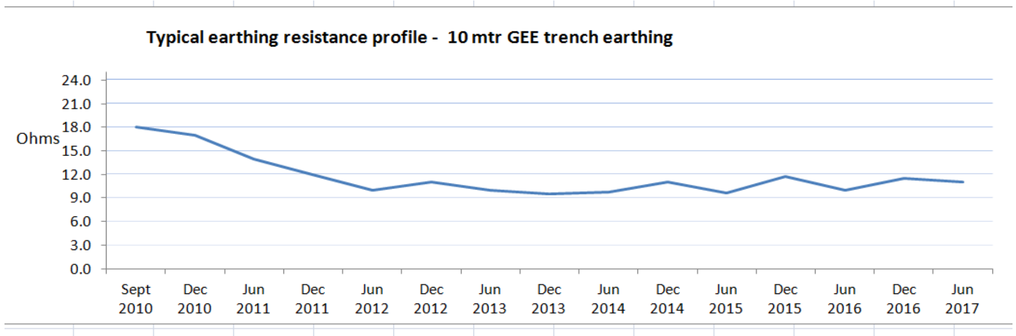
Using the above formula, Table 5 below provides the calculated *Earthing* resistance for various GEE *Earthing* lengths and soil resistivity. Coefficient K=0.7 has been assumed in the calculations. K depends on the quality of installation (E.g. rock content in the trench, the quality of backfill soil used).

Table 5 : ***GEE slab Earthing resistance (by GEE Earthing trench length)***

Soil resistivity (Ohm-m)	*Earthing* resistance (Ohm)			
GEE slab Earthing length (m) ----->	***5m***	***10m***	***15m***	***20m***
50 Ohm-m	6	4	3	2
100 Ohm-m	12	8	6	5
150 Ohm-m	19	12	9	7
200 Ohm-m	25	15	12	9
250 Ohm-m	31	19	14	12
300 Ohm-m	37	23	17	14
400 Ohm-m	49	31	23	19
500 Ohm-m	62	39	29	23
750 Ohm-m	93	58	43	35
1000 Ohm-m	124	77	58	46

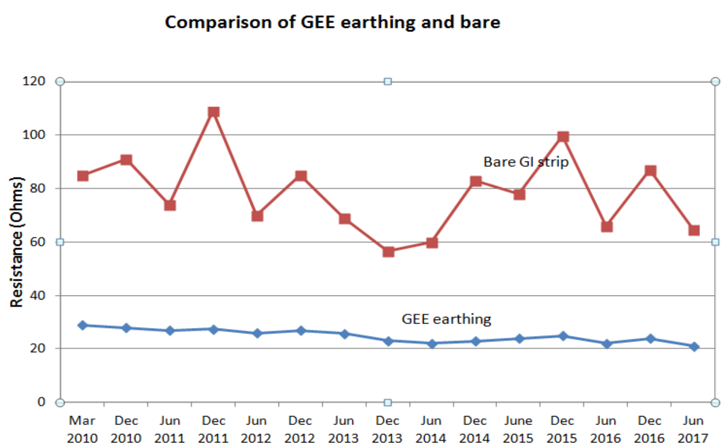
The effectiveness of GEE *Earthing* technology can be gauged in Table 5 above. For instance, it is evident that a 10 meter long GEE *Earthing* installation will provide a lower *Earthing* resistance than a quadruple pipe/rod electrode *Earthing* installations for a given soil resistivity. Besides being able to provide lower *Earthing* resistances, GEE *Earthing* technology is also different from the others because of its ability to provide a stable *Earthing* resistance (i.e. with minimal variation) throughout the year in a maintenance-free manner. In addition, durability (i.e. much longer life span) is also an inherent attribute (primarily because the conductive metal particles, fibers, meshes, and conductors, are encased and protected by concrete).

In order to prove that GEE *Earthing* slabs provide: (i) a reliable, durable, and maintenance free *Earthing* installation, and (ii) a much better alternative than most *Earthing* technologies, the test results (over the last seven years) of an actual installation is presented in the graphs below.



The graph above shows the performance of a GEE slab *Earthing* installation (i.e. 6 slabs) from September 2010 to June 2017. The soil resistivity is in the order of 250 Ohm-m. As can be seen, the *Earthing* resistance gradually decreases over time (i.e. in tandem with natural soil compaction) and has stabilized to around 10-11 Ohms. The stabilisation period would have been greatly shortened if soil compaction was done by pouring lots of water and compacting the soil at the time of installation. It may be noted that the number of GEE slabs necessary for an *Earthing* installation will depend primarily on the soil resistivity and the *Earthing* resistance value required by the *Earthing* application.

Further, in order to prove the effectiveness of encasing *Earthing* conductors in conductive concrete, a study was conducted (over last seven years) comparing the performance of: (i) 4.7 mtr GI flat directly buried in the ground, and (ii) 4.7 mtr GI flat encased in GEE conductive concrete and buried in the ground adjacent to the first. The results are self explanatory as seen in the graphs below.



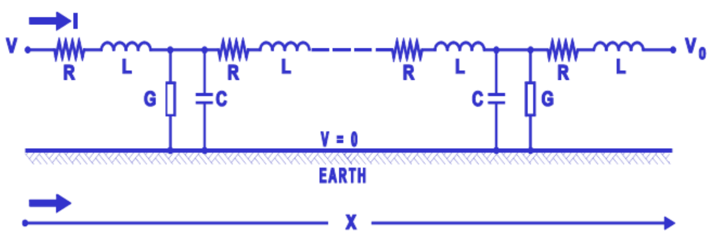
The performance graphs (left) compares (i) 4.7 m long GEE *Earthing* and (ii) 4.7 m long GI strip *Earthing* (i.e. bare conductor buried in soil).

Note: The two test installations are adjacent to each other so that soil resistivity is the same for the two.

The main important points in the graphs above are: (i) GEE *Earthing* provides much lower *Earthing* resistance than GI strip *Earthing*; and (ii) GEE *Earthing* provides a stable *Earthing* resistance while the strip *Earthing* provides a greatly fluctuating *Earthing* resistance between wet and dry seasons.

3. Ability to efficiently dissipate lightning and switching surges

Due to the transient nature and high frequency components of faults, an *Earthing* installation must provide a low impedance (rather than low resistance) path to efficiently divert faults into the ground. In an event of a surge due to a line fault, a power network switching operation or due to lightning strike, the electrode's capacitance and inductance (in addition to resistance) greatly influence the response of *Earthing* electrodes. Lightning strikes can deliver momentary spikes of 200 kA, 100 MV lasting a few micro seconds with its frequency spectrum ranging from 0 Hz to 10 MHz or higher. The rate of change of current (di/dt) can exceed 100 kA/microsecond. Therefore, the ability of *Earthing* installations to effectively dissipate lightning impulses and power switching surges is of paramount important. The performance of the various types of *Earthing* electrodes discussed above can be theoretically evaluated from surge impedance comparative assessment. The response of *Earthing* electrode to a power surge is more accurately represented by the lossy transmission line model as illustrated below.



The Characteristic Impedance (Z):

$$Z = \frac{\sqrt{R + j\omega L}}{\sqrt{G + j\omega C}}$$

Where: R = Resistance, L = Inductance, C = Capacitance, G = Conductance
ω = Angular frequency (2πf), j = imaginary unit

From the above formula, **R** is a function of material used for grounding, **L** and C are Inductance and Capacitance posed by the earthing installation, and **G** is earth conductance related to soil resistivity and contact resistance between earth electrode and soil. From the formula, it is evident that in order to minimize the impedance (Z), it is essential to minimize R and L and to Maximize G and C. Therefore in order for an *Earthing* installation to efficiently dissipate switching and lightning surges, it must have low R and L, and high G and C. While Inductance (L) can be lowered by minimizing sharp bends and conductor lengths for all electrode types, Capacitance would vary greatly between electrode types (i.e. directly proportional to the electrode surface area in contact with soil). Resistance (R) and conductance (G) would also vary greatly between electrode types (i.e. directly proportional to the electrode to soil contact resistance).

From the various *Earthing* electrode types reviewed above, GEE slabs provide the largest surface area (just one standard GEE slab provides 2.7 times the surface area of a standard pipe electrode. Therefore chain-linking a few GEE slabs will provide so much more surface area and consequently results in greater capacitance than any of the other *Earthing* electrodes discussed above. In addition, the large surface area in contact with the soil and also the better bonding between hygroscopic conductive concrete and soil, reduces the soil-contact resistance. This results in lower R and G. Therefore, GEE slabs will provide lower surge impedance than any of the *Earthing* technologies discussed above. It is also well established through actual laboratory tests that *Earthing* electrodes embedded in conductive concrete (E.g. San-Earth, Earth-Link) provide a much lower surge impedance than other *Earthing* electrodes such as counterpoise *Earthing* wire and rods.

4. Discussions and Conclusions

Although there are applications where high impedance *Earthing* is desired (i.e. to restrict the magnitude of fault currents), most applications in our LV distribution system (including consumer installations) invariably require a persistently (i.e. reliably) low impedance *Earthing*. Conventional salt based *Earthing* installations may provide low resistance *Earthing* in favourable soil conditions (i.e. at least until some salt remains or until the electrode corrosion is not significant), the important point to note is that such installations are not reliable nor durable. Unfortunately, the majority of the existing thousands of *Earthing* installations are forgotten after initial inspection when newly installed. Generally a bad *Earthing* installation is only discovered after an electrical hazard has occurred. Given the above facts and analysis showing that conventional *Earthing* is neither reliable or durable, it is opportune for the concerned authorities to urgently mitigate the risks and impacts of the existing thousands of salt-charcoal based electrical earthing installations that must surely be defunct (i.e. ineffective). Although the risks and impacts of such ineffective *Earthing* installations are substantial, the evaluation and analysis of the risks and impacts are beyond the scope of this paper (this will be addressed separately in another paper).

In the above calculations and comparisons, a homogenous soil (i.e. the same resistivity for the entire *Earthing* installation site) has been assumed. In reality, soil resistivity could vary even within an installation site. However, a homogenous soil of a fixed resistivity has been assumed to enable the objective comparison of the various *Earthing* technologies. Comparisons between *Earthing* technologies would be meaningless if the soil conditions are different. From the above comparisons and actual field data, it is clear that unlike the other *Earthing* technologies (i.e. vertically buried electrodes such as pipes, plates, and rods, or horizontally buried strips), Ground & Electrode Enhancement (GEE) slabs provide a much more reliable and durable means of *Earthing*. Another distinct advantage of using GEE slabs is its ability to provide lower surge impedance which is indispensable in order to efficiently dissipate damaging transient faults (E.g. due to switching surges and lightning strikes).

The following are some of the main lessons/issues to be pondered over.

(i) The reasons why salt-charcoal based *Earthing* installations are neither reliable nor durable has been explained (supported by factual data) in section 2.1 above. Because of its unreliable performance and short life, salt-charcoal based *Earthing* should ideally not be allowed by policy and regulation given the safety implications and many other negative impacts (viz; on power supply quality, on electrical machines/equipments, on consumer electrical appliances, impacts on ICT, etc).

(ii) Using the standard formulae for pipe/rod *Earthing* in Sections 2.1 and 2.2 above, it is evident through calculations that pipe/rod earthing will not provide adequately low *Earthing* resistances (let alone low impedance) in poor soil conditions (i.e. high soil resistivity). It is also clear that installing a few *Earth* rods (single or multiple) will seldom provide the required low *Earthing* resistance in unfavourable soil conditions.

(iii) Section 2.3 above shows by calculations that for vertical pipe *Earthing* electrodes, even increasing the electrode diameter substantially to 30 cm by encasing in very conductive material will not provide an efficient mean for electrical *Earthing* in poor soil conditions. Even a 10 m *Earthing* strip buried horizontally at a depth of 2 ft will provide lower *Earthing* resistance than a vertically installed pipe electrode (2.5 m long and 4 cm dia) encased in a very conductive material (with effective electrode diameter of 30cm).

(iv) Section 2.4 above shows that horizontally laid *Earthing* electrodes provide a more efficient means of electrical *Earthing* than vertically installed *Earthing* electrodes. For instance, a 5 m horizontally buried *Earthing* strip (i.e. 1 inch wide) at a depth of 2 ft will provide a lower *Earthing* resistance than a standard single pipe electrode (i.e. 2.5 m long and 4 cm dia pipe). However, while horizontally buried *Earthing* strips are clearly more cost efficient, it will also not provide a stable *Earthing* resistance (but will instead vary significantly between wet and dry seasons).

(v) GEE *Earthing* slabs (horizontally laid and connected) not only provide the most efficient means of *Earthing,* but also provide a stable (i.e. minimal fluctuations) *Earthing* resistance throughout the year. The stable *Earthing* resistance is primarily derived from the large surfaced hygroscopic conductive concrete body in contact with the soil. Further because of the slightly alkaline conductive concrete body, the corrosion of the metallic components is deterred thereby making it very durable (just like how the steel rebar are protected by concrete in RCC buildings). It will also provide much lower surge impedance essential for efficiently dissipating damaging transient faults.