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Comprehension of Energy-Based Methods for Investigating Soil Suffusion Uncertainties

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ABSTRACT

This paper delves into the contemporary landscape of suffusion investigation in soil, with a specific emphasis on energy-based methods. Recent research endeavours, notably have significantly advanced the discourse in this domain by proposing the utilization of the erosion resistance index, and introduced a novel energy-based method, both aimed at elucidating suffusion susceptibility. Building upon this foundation, some researchers conducted a comprehensive exploration of factors influencing suffusion. Notably, confining pressure and fines content emerged as pivotal variables exerting a substantial impact on the phenomenon. This understanding underscores the multifaceted nature of suffusion and its sensitivity to specific soil characteristics. In addition, researchers contributed to the literature by developing a discrete numerical model, providing a computational framework to investigate suffusion initiation and its subsequent effects on soil mechanical properties. This modeling approach adds a valuable dimension to the existing methodologies, enabling a more granular examination of suffusion dynamics. In concert, these studies collectively underscore the paramount significance of energy-based methods in both understanding and predicting suffusion in soil. The amalgamation of diverse approaches not only enhances our comprehension of the intricacies involved but also positions energy-based methods as instrumental tools for advancing the field of soil mechanics. This review consolidates these insights, providing a synthesized overview of the evolving landscape in suffusion research and highlighting avenues for future exploration and refinement of energy-based methods.

1. INTRODUCTION

Internal erosion can take many different forms, can seriously endanger both human and animal life, and is capable of doing great harm to infrastructure. Piping and suffusion are two appearances of internal erosion [1]. Different processes result in erosion, each of which is capable of causing destruction [2]. Suffusion, also known as internal instability, is a long-term phenomenon whereby small soil particles are carried away by a soil seepage flow through spaces between larger ones [3]. It indicates that a soil matrix's particle size distribution and the selective erosion of tiny particles from it do not match the requirements for self-filtering [4]. Suffusion is more prone to arise in coarse, widely graded or gap-graded soils (such as some sandy gravels) [5-7]. Internal instability is a common term used to characterize soils that are prone to suffusion [8]. Suffusion, which is caused by seepage forces, is the mass movement of fine particles through the pore space of a coarser matrix shown in Figure 1.

Internal erosion of levees, earth dams, and foundations as well as watershed hillslopes is mostly caused by it [2, 9, 10]. The impact of internal suffusion on a soil stratum's permeability, volumetric behaviour, and shear strength as well as the gradation are particularly concerning geo-mechanical soil parameters [11, 12]. Additionally, soil settlement has been connected to harm to earthen structures, buried utilities, buildings, and other structures [5, 13, 14].

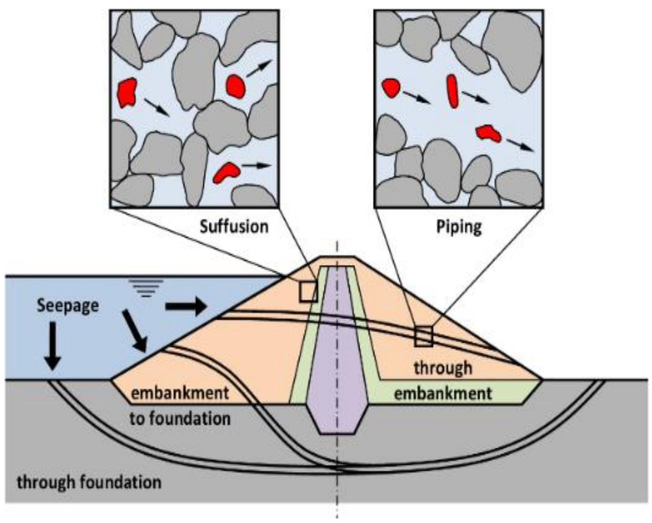

Figure 1. Internal erosion process

The long-term impact that suffusion may have on the possibility for volumetric change to occur within a soil layer and the change in compressive strength is largely unexplored elements of geotechnical science. Additional knowledge on these internal erosion-related subjects can help with our understanding of the underlying mechanisms and processes, which will improve the way many earthen hydraulic structures are designed and protected from erosion's destructive impacts. Therefore, one of the primary mechanisms of internal erosion is suffusion, which results in selective erosion and progressive movement of tiny particles through the spaces in the soil skeleton created by coarse particles during seepage flow shown in Figure 2. Many hydraulic geo-structures, including embankment dams, dikes, levees, landslide dams, and natural deposits, exhibit seepage-induced suffusion [15, 16].

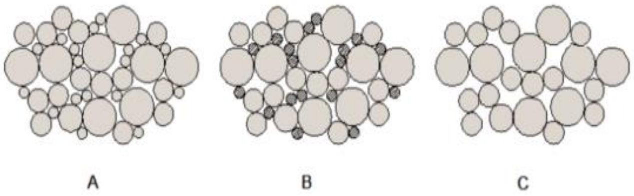

Figure 2. Progression of suffusion. (A) The fine particles attached with coarser particles with a seepage line (B) The starting of suffusion influenced by seepage and (C)The suffusion in which the fine particles flow with the seepage creating the voids [17]

ERT is a quick and efficient non-destructive measurement technique for acquiring continuous soil subsurface resistivity profiles which is used in this study. Moisture variations and soil heterogeneities can be found using an ERT approach. ERT is becoming a prevalent tool in the field of geotechnical engineering [18]. However, at this time, it only offers qualitative data. It can be difficult to determine quantitative geotechnical information about the subsurface from qualitative images, such as the moisture content, kind of soil, saturation degree, and Atterberg limits [18-21]. Numerous studies have explained how pore fluid conductivity and surface conductance affect the electrical resistance of soil. To ascertain the impact of geotechnical features, electrical resistivity experiments have also been performed on commercial soils [3, 22-25]. Electrical resistivity must be associated with geotechnical parameters that can be measured in a laboratory because pore water and surface charge characterisation studies cannot be performed during a standard geotechnical investigation.

Many research conducted in recent years to investigate suffusion susceptibility and its relation to hydraulic conductivity [26-29]. This research however aimed to relate soil porosity and ground motion, in contrast to others, simply because the initiation of suffusion breaches or soil failures by suffusion are similar, hydrologically or seismically, and soil porosity (void ratio) is the cause of soil instability. By correlating soil porosity (void ratio) and ground motion via suffusion factor (SF) and amplification factor (AF) then alternative method of attaining soil properties via electrical resistivity test (ERT) for this study apart from boreholes or standard penetration test (SPT) to analyse suffusion can be proposed. With this correlation and proposal, ERT can be independently deploy to investigate suffusion and its potential consolidation/settlement subsequently can be used as supplementary coefficient or multiplier to factor of safety (FOS) in slope design.

2. MOTIVATION

The world has experienced soil failures due to internal soil instability caused by suffusion, including dam failures in the US, railway embankment failure in Southern Italy, and damage to homes, roads, and railroads during the 2007 Noto Hanto earthquake [30, 31]. In addition, all earthen constructions, including river levees, roads with cut slopes, dams, and retaining walls, are seriously threatened by internal erosion phenomena. The inability to witness and monitor these events since they take place within the material has hampered the study of these phenomena. Non-destructive geophysical monitoring methods like ERT are effective tools that can shed light on the underlying processes [13].

Various research has been carried out on internal erosion of soils by but earthquakes have not been incorporated in the suffusion. Our infrastructure heavily relies on earthen structures, thus geotechnical engineers need to be aware of all the dangers they offer as well as how well they can function. There is a lot of information available about internal piping erosion processes. Suffusion and its long-term impact on the functionality of an earthen construction under the influence of earthquakes, however, are mainly unexplored. A safer design and construction of this vital piece of infrastructure may be possible with more understanding. The lack of proper consideration of this phenomenon had resulted to soil defects and failures on cut-slopes that subsequently damaging to the economy and ecology.

3. LITERATURE REVIEW

3.1 Issues causing soil failures

Shan and Ke [32] re-examined the soil's failure in a lab setting using an undrained cyclic loading test to show several patterns of failure. Fine-grained soils typically perform poorly and exhibit "cyclic motion with liquefaction" in their behaviour. When compared to traditional fine-grained soils, collapsing failure is clearly visible in fine-grained soils. In actuality, the fine-grained soils' clay content, plasticity index, and water content to liquid limit ratios range from 3.0 to 20.0 percent, 0 to 9.6, and 0.85 to 1.11, respectively. There is some regularity in the particle size characteristics of the fine-grained soils with a collapse failure feature, according to the analysis of the soil indices for these soils [8, 27-30].

The strain on all types of soil samples is quite low and oscillates about the x-axis in the early phases of the cyclic loading. When the axial (or shear) strain reaches a high strain level after a critical cycle, the samples reach a failure state. The excess pore water pressure of the fine-grained soils rises significantly in the first few cycles before gradually rising [31]. However, after a critical cycle, the extra pore water pressure begins to build up and finally reaches a relatively high level. The rate of reduction in the effective stress is quite rapid at the start of the loading stage and thereafter becomes roughly constant, correlating to the excess pore water pressure. As soon as the effective cyclic route reaches the critical cycle and the samples satisfy the required failure conditions, the rate of effective stress reduction immediately increases. The characteristic of the fine-grained soils' collapse failure is shown by the hysteresis curves. Unlike the relatively little deterioration of stiffness in the early stages of the cyclic loading, the substantial loss of stiffness of the fine-grained soils arises shortly after a critical cycle. As cyclic loading cycles increase, viscous energy dissipation (VED) initially climbs significantly during the first one or two cycles before steadily declining until the minimal VED values are obtained. When the peak VED values are attained, the VED rises until the final stage of the cyclic loading, where the VED values quickly decline from the peak within a few cycles [32].

Five different types of their dynamic qualities help to explain how fine-grained soils with a collapse failure feature function. Furthermore, in the last phase of cyclic loading, every dynamic property displays a clear indication of collapse failure. Both the current classification criteria for soils, according to American Code and British Code (ASTM 2017-e1; BSI 2015), and the criteria for the liquefaction susceptibility of fine-grained soils highlight particle size characteristics as one of the soil indices.

$$\begin{aligned} d_{\mathrm{G}} &= \Sigma^{n_1}\sqrt{d_1^{n_1} \times d_2^{n_2} \times \cdots \times d_i^{n_i}} \\ &= \sqrt[3]{d_{10} \times d_{30} \times d_{60}} \\ &= \sqrt[3]{C_{\mathrm{u}}} \times \sqrt[3]{d_{10}^2 \times d_{30}} \\ &= \frac{d_{30}}{\sqrt[3]{C_{\mathrm{c}}}} \end{aligned} \tag{1}$$

Therefore, d_G can be utilised to discriminate between the liquefaction behaviour of sands and the collapse failure of fine-grained soils. DG is the grain diameter, which allows to describe the nature of the grains, the fine is the grain, and the compacted is the mass, when it comes to higher diameters i.e., coarse grains leading to higher voids, in turn increases the threat of instability. The Atterberg limits are frequently regarded as important indicators of soil strength and behaviour attributes. For instance, Seed and Idriss [33] used the plasticity index (PI) to separate the behaviour of fine-grained soils that behaved like sand (PI 7) and clay (PI 7) for geotechnical engineering and practice. Additionally, it was suggested by Seed and Idriss [33] that one of the key criteria for determining which fine-grained soils are prone to liquefaction is a plasticity index (PI) of less than 12. Furthermore, a liquid limit (LL) of less than 32 and 37, respectively, was indicated by Slangen and Fannin [10] and Seed and Idriss [33] as the crucial factor that determines the susceptibly liquefiable fine-grained soils. It is commonly acknowledged that soil strength is closely connected to its water content (Wc). Therefore, in this context, the ratio of the soil's water content to its liquid limit (Wc/LL) and the liquidity index (LI), which is defined as (Wc - PL)/(LL-PL), are typically regarded as the key indicators to reflect the likelihood of the soils' strength loss. Higher density and greater strength of a soil sample are represented by lower values of the Wc/LL or LI. It has been discovered that the fine-grained soil failure envelop lies within the indexes Wc, PI, and Wc/LL range, respectively, from 3 to 20 percent, 0 to 9.6, and 0.85 to 1.11 [32, 34-36]. Figure 3 of a Venn diagram created by Moffat et al. [37] to demonstrate how soil collapse begins when one or more of the following factors occur or coincide in an unfavorable way:

- Material susceptibility
- Stress conditions
- Hydraulic load

Their research indicates that the term the relative erosion resistance of the soil, or the plasticity index of the soil, is another important factor in "material susceptibility." The hydraulic energy required to trigger an internal erosion mechanism through seepage flow through an embankment is known as the critical hydraulic load. In other words, this issue has to do with whether the embankments or foundation's seepage gradients and velocities are sufficient to start particle movement.

With understanding that stress changes geographically and/or temporally within an embankment, the capacity to resist internal erosion caused by the magnitude of effective stress is linked to the critical stress condition. Internal instability is affected by the stress condition, which can also be seen as showing the presence of "defects" in an embankment or foundation, whether these are brought on by cracking, hydraulic fracturing, arching, or other similar occurrences. The zone of the embankment that is vulnerable to all three elements is described in the centre subset. Material susceptibility, hydraulic loading, and critical stress combine to produce the release or detachment of soil grains as well as their movement.

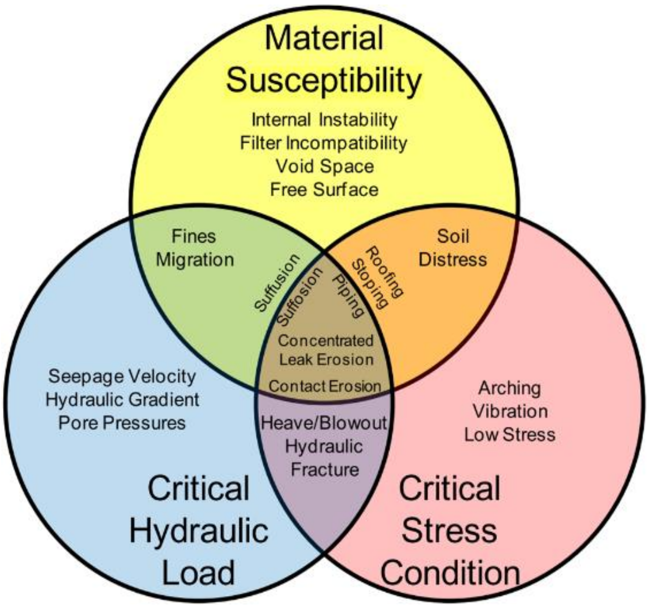

Figure 3. Illustration of initiation of soil failure [37]

3.2 Common property shared within all causes of soil failure

Issues causing soil failure are well presented by Shan and Ke [32] research. From soil mechanics stand point via soil phase diagram, bands of soil properties contributing to instability of soil were tested, analysed and concluded. All soil properties specified i.e., clay content classified as fine-grained soil, plasticity index range that indicate soil mixture proportion and liquidity index are very much related to the volume of void (Vv) and the variation of volume of air (Va), volume of water (Vw), combined [38]. Osman et al. [39] findings are complimentary to Shan and Ke [32] research where estimating clay content and plasticity index are attainable with electrical resistivity value. This study demands for possibility to estimate the LL, Wc and LI to complete the correlation accordingly.

According to Jaimes et al. [40], 3 main sources of information needed to identify an area susceptible to liquefaction:

- Historical information as evidence

- Hydrological and geological surroundings
- Geotechnical and/or geophysical analyses based on experiments that have been carried out.

Jaimes et al. [40] stress that soil vulnerable to liquefaction has certain geology and geotechnical properties. The soil deposits most prone to liquefaction are those with minimal cohesiveness (such as fine sand and fine sandy silt). Consequently, sands with very little flexibility correspond to natural soil deposits with greater sensitivity to liquefaction. Evidence suggested that gravels in saturated soils are typically loosely deposited in a silt or sand matrix that is susceptible to experiencing soil failure and was greatly impacted by liquefaction during big earthquakes (e.g., 2008 Wuhan, China earthquake).

Both natural deposits and filled embankments have been found to exhibit suffusion, an internal erosion, in large quantities [4, 30, 41, 42]. The soil skeleton is eventually left behind as fine soil particles migrate via spaces between the larger soil particles [8]. Due to their lack of particle size, gap-graded and broad-graded cohesionless soil is particularly susceptible to internal erosion. Internal erosion is indicated by the loss of tiny particles, which changes the void ratio and considerably increases hydraulic conductivity, lowering the soil's capacity from its initial strength [43]. Suffusion is described as a vast mass of dispersed and hardpan detrital species, including those that make up the structural parts of rocky massifs, and damaging and fine particles carried by a stream of underground waters, in accordance with Russian Standard CR 116.13330.2012.

Suffusion can develop cavities through migration and dispersal of fine particles of soil relating to various soil types can be a big threat to soil-structure interaction [44]. If designed facilities are not located in hazardous karst regions, coastal areas of reservoirs, or slopes that are prone to landslides, industrial and civil engineers may ignore the risk of a suffusion during construction and maintenance.

Thermal monitoring allows for the identification of the suffusion process due to distinctive changes in the dam's hydrothermal environment. Despite the fact that little research has been done on the post-erosion mechanical effects under monotonic shearing, the effects of suffusion on the cyclic resistance and liquefaction potential of internally unstable soils have received little attention. Because eroded specimens with lower intergranular void ratios exhibit superior resistance during cyclic loading, understanding the intergranular void ratio is essential for understanding the mechanical behaviour of soils post erosion.

3.3 Suffusion shared common caused to soil failures by mean of the following

The size of the tiny particles is less than the size of the spaces between the coarse particles that make up the soil's skeleton, and there are not nearly as many fine particles as there are voids to fill. The fine soil particles can migrate through the spaces between the coarse particles because the hydraulic gradient (hydrologic) is reasonably big.

A seismic event, such as an earthquake, results in deformation (rapid migration through vibration, filling of spaces between larger particles, and/or fracture that would start internal erosion) [1, 45, 46]. Granular soils' mechanical properties change when they are subjected to seismic loadings. There are two extremes in terms of soil saturation: dry soil and saturated soil, which can lead to densification and liquefaction events, respectively. The solid skeleton rearranges as the shaking goes on, leading to densification. As a result, the initial soil volume is reduced, and the soil stiffness frequently rises [47-52].

Ogbobe et al. [52] and Koerner and Koerner [53] presented on research on employing geotextiles and geosynthetics to increase the safety against suffusion and erosion in an embankment. In general, materials with $Cu < 10$ were regarded to be self-filtering, whereas those with $Cu >20$ were deemed to be possibly unstable [54, 55]. A local gradient reduction that is temporally compressed can indicate instability. The primary determinants of the location of instability inside a site-specific are spatial variation of localized hydraulic gradient and vertical effective stress, with internal instability being triggered either by an increase in hydraulic gradient or by a fall in effective stress. When suffusion erosion started, permeability dropped, indicating blockage. Suffusion was examined by Bonelli and Marot [56] as bulk erosion, where clayey sand erosion took place at the clay-water contact. Macroscopic bulk erosion is driven by the pressure gradient rather than the seepage velocity for the migration to occur.

Further from the literature review, the direction of identification of common phenomenon shared within all caused of failure is drawn towards suffusion and common property in suffusion is void or porosity.

3.4 Electrical resistivity of soil and identification of void ratio/porosity of soil

The spatial and temporal variability of a variety of other soil physical characteristics can be substituted by the electrical resistivity of the soil (i.e., structure, water content, or fluid composition). Because it is non-destructive and exceedingly sensitive, the method offers a very appealing instrument for documenting the underlying structures without excavating [18, 57]. It has already been used in a variety of contexts, including groundwater exploration, landfill and solute transfer delineation, agronomical management by locating areas of excessive compaction, determining the thickness of the soil horizon and the depth of the bedrock, or at the very least evaluating the hydrological properties of the soil [58].

Archie's law outlined how the porosity of rocks and their electrical conductivity relate to one another. It is believed that all conduction happens only through the pore-solution and that the rock itself is non-conductive [59]. But very little work has been done by researchers to determine whether Archie's law applies to soils [59]. Therefore, this study application of Archie's rule for soils which takes into account their physical characteristics, volumetric moisture content, and apparent resistivity was made possible by the information gathered in locations between Serian and Sri Aman in Sarawak. To further support the legitimacy of this law, twenty-one (21) samples of soil were used, attained from an undisturbed location where no known induced compaction nor consolidation taken place before the construction of Pan Borneo Highway of Sarawak. These soils have been tested and characterized accordingly by conventional laboratory tests, and their apparent resistivity were captured via electrical resistivity test (ERT).

Before any soil, the complete void can be represented by its liquid limit when it experiences an elastic settlement in a natural setting outside of a lab that is brought on by the elastic deformation of both dry and moist of saturated soils without affecting the moisture content of either [5, 60]. This is due to the fact that the soil's shift from a liquid to a plastic state occurs at the liquid limit, which is an empirically determined moisture level. When a soil is dried in an oven at a temperature no greater than 110℃, the amount of water present in the gaps between soil grains is measured as the soil's moisture content [25, 61-63]. The amount of moisture has a significant impact on how the soil behaves. Therefore, the amount of the total soil volume that is occupied by the pore space, also known as soil porosity, and the moisture content from liquid limit occupy the same volume [13, 16, 60, 64]. Hence, from ERT one can determine the soil porosity which is equal to liquid limit of that particular soil. Additionally, this makes a significant contribution to the prediction of a soil's elastic settlement (Se), primary consolidation (Sc), and even secondary consolidation (Ss).

Archie's first law is a tool used in petroleum engineering to determine the cementation exponent of rock units. The volume of hydrocarbons in the rocks may then be determined using this exponent, allowing for the estimation of reserves [65]. It is considered that Archie's Law does not apply to rocks that include a sizable amount of clay. One of the key presumptions is disproved by the conductive matrix that clay offers. Electrical conductors can also be found in graphite, native metals, and minerals with metallic clusters, however these materials are much rarer than clays [59, 65]. Archie’s law is given by the below equation:

$$\rho o = \rho f\, \varphi - m \tag{2}$$

where, ρo is the resistivity of a rock sample that has been completely saturated with water, ρf is the resistivity of the water that has saturated the rock's pores, φ is the rock's porosity, and m is the cementation exponent [59]. At least nine out of ten times, however, reservoir engineers and petro physicists do not use Archie's first law in this manner. Instead, they employ a slightly modified version that Rousseau et al. [60] published ten years later, and which has the form:

$$\rho o = a\rho f\, \varphi - m \tag{3}$$

where, also known as the "lithology constant" or the "tortuosity constant," is an empirical constant. In actuality, neither the new characteristic which we'll refer to as a parameter nor the rock tortuosity or lithology are related [59]. It is intended to account for variations in grain size, pore structure, and compaction [65, 66]. The path length of the current flow is obviously related to the tortuosity factor, often known as the parameter ‘a’. The value lies in the range 0.5 to 1.5 [65] and since the test site for this study involving undisturbed area therefore value a = 0.5 is used. Almost always, the minerals that make up a rock are electrical insulators. Electrical conduction is consequently possible because of the moisture that exists in the pores of the rock and soil. Several factors affect the resistivity of rocks and soil. These include the amount of clay present, the moisture salinity, the level of pore saturation, and the quantity, dimensions, and morphology of the interconnecting pores.

Porosity of soils is influenced by the degree of compaction, which is another crucial element. Archie established the empirical formula below in 1942 and it connects resistivity to porosity, saturation level, and resistivity of the saturating moisture [67].

$$\rho o = a\varphi - ms - n\rho w \tag{4}$$

where, φ is the fractional pore volume (porosity), s is the percentage of the pores that contain water, ρw is the water's resistivity, and n is about 2. a and m are constants, changing from 0.5 to 2.5 and from 1.3 to 2.5, respectively. Since the electrolyte in the pores of soil and rock is used to conduct current, the porosity, or void ratio, of the material and the geometry of the pores play a significant role in determining resistivity. Intergranular voids, joint or fracture holes, and blind pores, such as bubbles, are examples of the several types of pores that can exist. Only the interconnected pores effectively contribute to conductivity, and this contribution is further influenced by the geometry of the interconnections or the tortuosity of the current paths. Factors influencing electrical conductivity in rocks and soils are:

- Porosity (connected/effective - fractures or pores)
- Pore saturation (% air or gas)
- Hydrocarbon Fluid Saturation
- Water salinity (TDS)
- Clay Content
- Metallic Sulfide Mineral Content
- Fluid temperature
- Rock Matrix intrinsic resistivity

With the exception of the cementation exponent (m), all of the aforementioned parameters can be determined by testing soil samples in a lab and using ERT. But as the rock becomes more tortuous (path length), tortuosity becomes more than 1. This links the cementation exponent to the rock's permeability; as permeability increases, the cementation exponent drops. For unconsolidated sands, the exponent m was found to be close to 1.3, and it is thought that it rises with cementation. This cementation exponent typically has values of $1.8 < m < 2.0$ for consolidated sandstones. Due to strong diagenetic affinity and intricate pore architecture, carbonate rocks exhibit a larger variance in the cementation exponent. Values between 1.7 and 4.1 have been observed [65].

Electrical resistivity can offer continuous measurements over a wide range of scales without causing any damage. This method allows for the monitoring and quantification of temporal variables without changing the internal soil structure, such as water and plant nutrients, which depend on it. Resistivity characteristics of geological targets [68] is shown in Figure 4. This method can be deployed to many engineering applications such as:

- Identifying the soil horizon and certain heterogeneities.
- Monitoring the transportation phenomena.
- In a saline or waste context, monitoring of solute plume pollution.
- Information regarding the physical characteristics of soil, such as its porosity and soil phases, can be obtained via electrical resistivity investigations (Table 1). Recent advancements in electrical technology enable quick spatial and temporal resolution.

Archie’s law:

$$\rho = a\ \Phi\ \text{-}m\ f\ \text{-}n\ \rho w \tag{5}$$

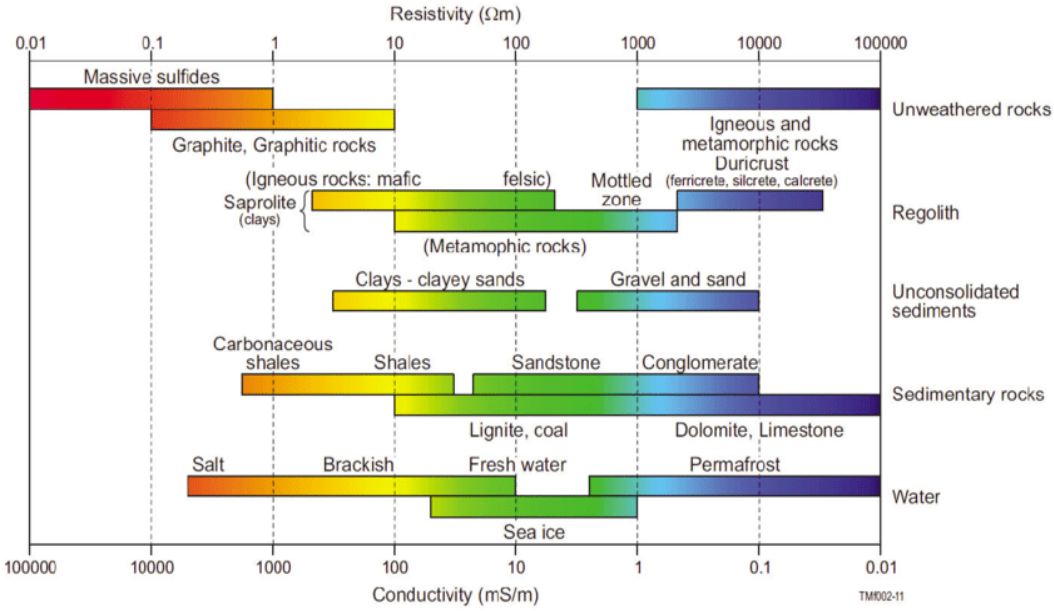

Figure 4. Resistivity characteristics of geological targets [68]

Table 1. Founded subsurface insights and published refined electrical resistivity [68]

Materials	Electrical Conduc. (mS/m)	Electrical Conduc. (µS/cm)	Electrical Res. (ohm.m)	Comment
Surface and groundwater	5-150	50-1500	6-200	Large variability
Sea water	3000-5000	30000-50000	0.2-0.33	Mean: 3270 mS/m
Unconsolidated material	10-1000	100-10000	1-100	Saturation & mineralogy dependence
Sedimentary rocks	1-200	10-2000	5-1000	
Igneous and Metamorphic rocks	0.1-10	1-100	100-10000	Weathering decreases resistivity
Clays	25-250	250-2500	4-40	Clay type and moisture important
Clayey soil (40% clay)	125	1250	8	Clay % decreases, resistivity increases

Important relationship related to site-specific resistivity value captured:

- Depth of study i.e. tomographic plot is equivalent to Electrical Resistivity Test (ERT) captured/reading or equivalent to ½ of total takeout cable length [69]. Many other soil physical parameters, such its electrical resistivity, can be thought of as proxies for the geographical and temporal variability (i.e. structure, water content, or fluid composition) [70-74]. The technique provides a very attractive instrument for describing the subsurface features without excavating because it is non-destructive and extremely sensitive. It has already been used in a variety of situations, including groundwater research, landfill and solute transfer delineation, agronomical management by locating areas of excessive compaction or soil horizon thickness and bedrock depth, or at the very least, evaluating the soil hydrological qualities [75-79].
- Porosity = Archie's law (Eq. (5)), equivalent to VV/V theoretically equals to soil liquid limit. Upon proven, by experimental procedure, Archie's law is valid for used in soil not just rock in Table 1.
- Soil bearing capacity = Linear regressions equation between bearing capacity and relative compaction. $y= Ax+87$, where x= allowable bearing capacity (kN/m^2); y = relative compaction (% or n) and A = FoS.
- $Vs = 23\ S_u 0.475$.
- PGA = Seismic Hazard Map.

4. FINDING GAP AND ADVANTAGES IN A SIMPLIFIED ANALYSIS WITH ERT DATA ACQUISITION TO DETERMINE LIMIT STATE OF SOIL STABILITY

It is possible to identify the hydrogeological conditions that are prevalent within the investigated area by correlating electrical resistivity with the available geologic information. Although porosity measurements lack the great accuracy of those performed in academic petro physics facilities, they are typically accurate and have a very good consistency to 0.5% i.e. 0.005 [59].

This study attempt to provide experimental evidence that porosity value, n is equal to volume of void (VV) over total volume (V) of sample taken which is aligned with the soil phase relationship and the small percentage of uncorrelated data is due to human-error such; recording data error; disturbed sample; laboratory equipment not calibrated and uncleaned; human act of not diligent during recording captured data, predict result of test without proper test due to the familiarity and other human mistakes. So far no recorded literature of study that attempted to correlate liquid limit of soil (LL) with soil porosity.

Additionally, it is noteworthy that electrical resistance, Ω, is equivalent to (conductivity)-1 where based from Archie's law, porosity or LL is consistent in electrical resistivity and electrical conductivity however actual reading at site-specific showing resistivity (at some points) are not the same with inverse conductivity or inverse sigma, $\Omega \neq [1/\Sigma]$. In a hypothetical situation, the volume of voids is consistent with electrical conductivity and resistivity, but tortuosity is different since it depends on the ratio of the curve's length (C) to the distance between its ends (L). And, hypothetically, electrical resistivity is equal to index volume of void in straight length (L) and electrical conductivity is equivalent to index of volume of void in curve length (C). Therefore, tortuosity (τ) value is attainable through this research where $\tau = C/L = [1/\Sigma]/\Omega$, or $\Sigma\text{-}1/\ \Omega$, or $\Omega/\ \Omega = 1$, when index of curve length = index of straight length. From this study, theoretically, water filling curve length void represent water content (Wc) and water filling straight length represent liquid limit (LL), where Wc/LL > 1 resultant with physical water discharged. Threshold value of soil plastic state changing to liquid condition is a precursor to soil failure and difficult to determine at site-specific. And in simple term, where Wc/LL > 1, one can be identified the failure line which only inclinometer can detect when soil strata moved and will be too late.

In limit state methodology, where actual resisting force versus allowable resisting capability, is desirable in this study due to capitalization of minimized uncertainties and promoting safety. Actual data of site-specific is reliably attainable with electrical resistivity test with no human interaction nor possibility of tempering with the actual data during acquisition and/or processing. Site-specific data acquired shall be processed with seismic interaction or energy-based methods to produce soil-amplification spectrum that comparable to Standard for identification of unstable soil.

The root cause of failure in geotechnical design is due to the information attained not site-specific, a few samples to represent all. The lowest band of weak soil layers may not represent the weakest segment of all sections. And the design to resist failure to that known segments may not be adequate for the other sections. Literature educated many of how to deal with weaknesses however the solution may not be the ideal answer because of the combination of site-specific situations and the affecting surrounding conditions. The needs to acquire underground comprehensive information is crucial to provide a better design. The literature provided us with Archie's law that measure soil porosity, resistivity, saturation exponent and cementation constant. Porosity in soil is linear to resistivity value and related to compaction degree of the soil. Resistivity value of soil is between 1 to 40 ohm.m and the correlation with degree of compaction and standard penetration test (SPT in blows) is achievable where the value is between 1 to 50 blows and a crucial criteria of strength in engineering properties, however the literature is yet to offer. The other important aspect in failure criterion of soil is the liquidity index (LI) i.e., equivalent to water content in soil (Wc) over liquid limit of soil (LL) where the literature has provided us the experimental information of unstable soil consist value of LI of higher than 0.85 (LI > 0.85 is the limit of unstable soil index). The only area that the literature is yet to provide is that LL is equal to volume of void (VV) over volume total (VT) where it is governed by porosity that attainable via Electrical Resistivity Test (ERT) and conduction of current (conductivity) in soil is through the electrolyte contained in the pores i.e., related to Wc which also can be acquired with ERT.

This study is intended to fill the gap of knowledge that is important to ascertain by ERT with comprehensive imaging without having to interpolate cross boreholes, data free from manual recording error, easily deployed, immediate results and tomographic image for future new findings interpretation. Better geotechnical design provision at site-specific to resist failure, counter-movement, filtering water to reduce pore pressure to the index of stable soil and identification of floating slab where borehole criteria to terminate but still layers of soil consist underneath which can induce delayed-failure. ERT, for this study, shall provide imaging for stable soil for foundation with SPT-N 50, rock layers, type of rock mass, weak soil layers and water content in soil.

5. DISCUSSION AND CONCLUSION

The literature review encapsulates recent strides in understanding suffusion in soil, with a primary focus on energy-based methods. The elucidation of energy-based methods by Salahou et al. [80] and Marot et al. [81] represents a significant advancement, providing alternative perspectives for determining suffusion susceptibility. The consideration of confining pressure and fines content as influential factors in suffusion, as explored by Liu et al. [82], adds granularity to our comprehension, highlighting the nuanced sensitivity of suffusion to specific soil characteristics. The introduction of a discrete numerical model by Tao [83] is particularly noteworthy, offering a computational lens to scrutinize suffusion initiation and its subsequent effects on soil mechanical properties. This modeling approach expands the methodological toolkit, allowing for a more comprehensive exploration of suffusion dynamics. The amalgamation of these diverse methodologies collectively underscores the critical role of energy-based methods in both understanding and predicting suffusion in soil. The multifaceted nature of suffusion, as indicated by the exploration of various influencing factors, attests to the complexity inherent in this phenomenon. The synthesized overview provided by this review contributes to the evolving landscape of suffusion research, emphasizing the instrumental role of energy-based methods. In conclusion, this review consolidates current knowledge on suffusion in soil, particularly emphasizing energy-based methods. The identified key methodologies, including the erosion resistance index, novel energy-based methods, and numerical modeling, collectively enhance our understanding of suffusion susceptibility and its influencing factors. The significance of suffusion in soil, exemplified by its potential impact on infrastructure and the environment, underscores the urgency for continued research and exploration. The integration of energy-based methods, such as electrical resistivity testing (ERT), represents a promising avenue for future investigations. ERT, despite offering qualitative data, emerges as a valuable tool for non-destructive measurements, especially in the context of understanding soil subsurface resistivity profiles.

The practical implications of advancements in energy-based methods for investigating soil suffusion are profound for real-world engineering and construction scenarios. Enhanced predictive models can lead to more accurate risk assessments for infrastructure projects, such as dams, levees, and embankments, where soil erosion and suffusion pose significant hazards. By understanding the precise conditions under which suffusion is likely to occur, engineers can design more resilient structures with targeted mitigation measures, such as optimized drainage systems or soil stabilization techniques.

Additionally, the ability to model suffusion more accurately allows for better maintenance and monitoring strategies, reducing the likelihood of catastrophic failures. For example, in the construction of foundations, tunnels, and other underground structures, improved suffusion prediction can inform the selection of appropriate construction materials and techniques, ensuring long-term stability and safety. Ultimately, these advancements can lead to cost savings by minimizing over-design and preventing costly repairs, while also enhancing the overall safety and reliability of critical infrastructure.

6. FUTURE RESEARCH

Future studies on soil suffusion ought to concentrate on improving energy-based techniques in order to more successfully handle uncertainties. This calls for the creation of increasingly complex models that can faithfully replicate intricate soil behaviours under various circumstances, such as various fines contents and confining pressures. It will be necessary to incorporate high-fidelity experimental data and sophisticated computational methods to improve the resolution and accuracy of these models. Furthermore, broadening the application of these techniques to include a wider variety of soil types and environmental circumstances will enhance predictive abilities and aid in the generalisation of results. To ensure that these models are practically applicable, field engineers and computational scientists must work together to validate them against real-world scenarios. Prioritising the creation of strong, practical tools for practitioners will help close the knowledge gap between theory and practice, which will ultimately result in more complete and dependable solutions for controlling suffusion risks in a range of geotechnical applications.

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