CHAPTER-7

SUMMARY OF FINDINGS

The post Barron developments in consolidation due to radial flow theories could be classified into two distinct approaches namely ‘free strain condition’ and ‘equal strain condition’ supported either by analytical solutions or numerical solutions. The consolidation phenomenon in soft soils due to radial flow cannot be tackled by mathematical treatments based on gross idealization. The consolidation problem is different from the elasticity problem and is not adequately solved by simply satisfying a heat conduction type equation. One of the distinct feature of the consolidation phenomenon is the occurrence of large volume changes during the process. A physical process, however, attractive it may be, loses its value if it cannot be mathematically exploited to evaluate the parameters for the engineering analysis. A clearer picture of the phenomenon is possible if a proper linkage between the physico-chemical characteristics of clays and analytical procedure is established. The Lagrangian mathematical scheme followed by McNabb (1960) and Gibson et al. (1967) is versatile.

A differential equation: 
\[
\frac{\partial e}{\partial T} = \left( \frac{r_e}{h} \right) \frac{\partial^2 e}{\partial R^2} \mp \lambda \frac{\partial e}{\partial R}
\] 
of Shroff and Shah (2008, 2010, 2012) for the present work is derived from fundamental consideration based upon the above mathematical treatment. The equation has form identical to the differential equation for the nonsteady one dimensional flow of heat through moving media against Terzaghi classical concept of heat flow through isotropic bodies.

Taking ‘\(\lambda\)’ as a constant, solution of the differential equation is obtained by Laplace Transform technique. Lumped parameter (\(\lambda\)) is the ratio of (\(C_e/C_r\)) \(r_e\) being \(C_r\) as coefficient of consolidation due to radial drainage and \(C_e\) as coefficient due to permeability and porosity. Change of tortuosity because of particle orientation under load variation reflecting soil structural changes (from edge to face and edge to edge or face to face) orientation is also accounted in lumped parameter (\(\lambda\)). Lumped parameter (\(\lambda\)) will vary with drain material, n’ value and shape of drain because of vertical strain in
Summary of Findings

the soil structure due to radial gradient of flow. For solution of higher order partial differential equation derived from first principles, an macro-EXCEL programme on computer is developed to compute theoretical relationships. The proposed theory is seen to agree adequately with experimental observations. The constant ‘λ’ of the equation emerges as a weighted factor to account for the deviation from Barron’s ‘equal strain’ idealizations. It is suggested that it will be worthwhile to obtain the solution of the differential equation taking ‘λ’ as some function of ‘t’.

The degree of exposition of any physical process depends on the degree of exactitude of the experimental set-up. Major factors that influence the measurement of consolidation characteristics are sample disturbance, side friction and inadequacies in the measuring systems. The present investigations show that deposition of uniform slurry at double liquid limit consistency in a pot produce a uniform sample, the smearing of silicone grease to contacting surfaces help minimize side friction, and continuous maintenance and calibration of measuring devices ensure precise readings. The use of electronic equipments demand stable electric power, constant temperature conditions and utmost vigilance for zero defects. The modified hydraulically pressurized Oedometer set-up is particularly better suited for pore pressure measurements and drainage control using central vertical drain. The measurement of local deformations and pore pressures within the clay bed using vertical drains employing displacement transducers, pore pressure transducers along with Bishop System interfaced with Data logger system connected to computer are worth a pursuit. Scanning electron microscopy of clay samples at various magnifications factors and use of Micro Structure Characterization (MIC) software helps to understand the role of various physico-chemical forces on consolidation characteristics of soft soil through radial flow under various vertical geodrains.

General Inferences:

1) There is a distinct behavior of soft soil during consolidation by vertical flow and only by radial flow.
2) Time – settlement curve (degree of consolidation) due to radial flow always lie below the vertical flow. This is because of shorter drainage path and horizontal permeability in radial flow compared to vertical flow.

3) Higher initial hydrodynamic lag is observed in dissipation of mid plane pore water pressure in vertical flow compared to radial flow. The tortuosity of soil structure for a vertical flow causes delay in the dissipation in early stage of consolidation.

4) Under lighter load time taken for the consolidation due to radial flow is 16 times lesser than the vertical flow, while for 50% consolidation time taken for radial flow is 3 times; for 90% consolidation time taken is about 6 times lesser than the vertical one which also reflects in coefficient of consolidation due to radial drainage ($C_r$) versus pressure relationship that is magnitude of $C_r$ decreases at faster rate compare to vertical one.

5) The void ratio for a particular load decreases at faster rate in radial case compare to vertical one. Initial structural dynamic viscosity of the soil configuration resist the light consolidation load exhibiting initial hump more in vertical case.

6) The measurement of coefficient of radial permeability of vertical drain using special set-up developed in present research is very useful in knowing the exact discharge capacity of any vertical drain of any ‘n’ value under constant head and falling head condition. This set-up is even useful to measure radial permeability of soil.

7) The modification of hydraulically pressurized Oedometer for measurement of complete pore water pressures by drawing three radial points at 120° each covering complete radial influence of soil sample has proved its efficacy at various stages of consolidation and by maintaining ‘equal strain’ condition with help of ‘rubber jack’ under various loadings gives better and accurate picture of influence of various parameters intended to affect consolidation of soft soils.

8) The studies on consolidation of clayey soil due to vertical flow revealed that degree of saturation, drainage path; stress history, mineral type and soil structure play their important role on settlement characteristics of kaolinitic clays, Shroff et.al (1972). The conclusions of present work are drawn considering the above factors and the influence of diameter (‘n’values), distinctive material and geometry of vertical drain with soil.
structure effects on consolidation characteristics of kaolinitic clay due to only radial drainage using hydraulically pressurized oedometer.

**Influence of Distinctive Drain Materials:**

1) **Rate of Consolidation**

*Degree of consolidation (Ur) vs. Time*

- From settlement and pore pressure measurement considerations it infers that for 50% consolidation, CJ under light loading takes 46% less time in compare to SW, 49% in compare to PF, 56% in compare to SD, while for 80% consolidation, CJ takes 31% less time in compare to SW, 35% in compare to PF and 44% in compare to SD and under constructional loading CJ takes 45% less time in compare to SW, 58% less time in compare to PF, 58% in compare to SD, while for 80% consolidation CJ takes 29% less time in compare to SW, 41% in compare to PF and 47% in compare to SD for same ‘n’ value and permeability ratio.

- Rate of drainage of a radial points nearer to drainage being faster the time taken for particular % of consolidation is less in compare to radial points farther away, it also reflects this observation in settlement measurements to some extent showing more compressibility gradient towards central drain. It seems from the micrograph of several drains the pore space in terms of nanomeasurement is larger compare to other drains. This reflects the efficiency of CJ with respect to micro structure opening even under light and heavy constructional loading.

- Under light loading for 50% consolidation SW takes 26% less time in compare to PF while it takes 0% against SD while SD takes 26% less time compare to PF but 34% more time compare to CJ. Similarly under constructional loading SW takes 41% & 3% less time in compare to PF & SD. Also SD takes 37% lesser time in compare to PF while SD takes 3% & 40% more time compare to SW and CJ.

- Under light loading for 80% consolidation SW takes 31% less time in compare to PF while it takes 3% against SD while SD takes 27% less time compare to PF but 23% more time compare to CJ. Similarly under constructional loading SW takes 30% &
Summary of Findings

5% less time in compare to PF & SD. Also SD takes 23% lesser time in compare to PF while SD takes 5% & 27% more time compare to SW and CJ.

- For any load intensity and drain material, the time deformation curve with respect to pore pressure dissipation remain towards the vertical axis compare to curve of settlement, that is time require for 50% or 80% consolidation is less compare to settlement curve which also reflects in isochrones curves. This is because of direction of flow from the void space is radial which allows early dissipation compare to particle reorientation achieving same degree of consolidation. The role played here is by ‘macrocompressibility’ in settlement case while ‘microcompressibility’ in pore pressure case.

- The gradient of radial flow is also facilitated by type of drain material, CJ drain may facilitate easy dissipation compare to other drain material, because of more percentage of microporosity in CJ drain compare to others which is also mentioned earlier in chapter 3 in para drain characteristics which also explains describes ‘permittivity’ and ‘transmitivity’ of various drain material used in fabricating the circular drain. Further this data indicate the gradient of water formed because of the higher or lower transmitivity of geosynthetics material used in the present investigation. In plane permeability data also confirms the above reasoning.

- Because of the above reasoning the time-deformation curve and isochrones indicate early dissipation and early deformation as well as the magnitude of vertical consolidation in CJ drain compare to other drains.

Coefficient of consolidation due to radial drainage ($c_v$) vs. Time

- Looking to above inferences it is clear that CJ shows more rate of consolidation both at low and high pressures in compare to other drain materials from settlement and pore pressure measurement considerations because of higher horizontal permeability of drain of CJ.

- Effectiveness of PF seems too remote from reality compare to functioning of other drains. While effectiveness of SW is less than CJ but higher then SD.

- Under any strain condition because of the flexibility CJ drain shows higher horizontal permeability compare to others.
Summary of Findings

- Cr for CJD for 50% consolidation from settlement readings work out to be averagely 73% & 78% more compare to other drain materials under light and heavy construction loading. Similarly for 80% consolidation it is averagely 63% & 66% more. This observation satisfies that higher horizontal permeability of CJD compare to other drain materials under light and heavy construction loading.

- Cr for CJD from mid plane pore pressure measurements for 50% consolidation work out to be averagely 154% & 155% more compare to other drain materials under light and heavy construction loading. Similarly for 80% consolidation it is averagely 48% & 81% more.

- For any load intensity and drain material, the time deformation curve with respect to pore pressure dissipation remain towards the vertical axis compare to curve of settlement, that is time require for 50% or 80% consolidation is less compare to settlement curve which also reflects in isochrones curves. This is because of direction of flow from the void space is radial which allows early dissipation compare to particle reorientation achieving same degree of consolidation. The role played here is by ‘macrocompressibility’ in settlement case while ‘microcompressibility’ in pore pressure case.

- The gradient of radial flow is also facilitated by type of drain material, CJ drain may facilitate easy dissipation compare to other drain material, because of more percentage of microporosity in CJ drain compare to others.

Coefficient of consolidation due to radial drainage \( (C_r) \) vs. applied pressure

- Under any strain condition because of the flexibility CJ drain shows higher horizontal permeability compare to others.

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SD = Sand drain, SW = Sandwick drain, CJ = Coir-Jute fiber drain, PF = Polypropylene fiber drain, \( n = \) ratio of drain diameter to soil sample diameter
Summary of Findings

- From the plots it is very clear that for all drain materials the initial nature of \( T_{r80} \) graph & \( T_{r50} \) graph decreases with initial applied pressure and at higher pressures it remains same that is nearly constant. It is because of the initial structural resistance existing in the clay water structure of the Kaolinite clay.
- Lesser variation in \( C_r \) value is observed for radial point’s \( r_2 \) and \( r_3 \) for all drain materials and for all applied pressures. Though CJ shows more inter-rate of dissipation of excess hydrostatic pore water pressure even at successive pressures in compare to other drain materials.

Isochrones

- From the consolidation ratio vs. radius of influence for various \( T_r \) values reveals that sequence of consolidation for CJ at any radius of influence seems to be efficient compare to all other drains.
- For all drain material experimental time factor more than 0.24 exhibit concave shapes initially, while \( T_r \) less than 0.24 shows convex towards vertical axis. Comparing isochrones for various drain materials it indicates that CJ shows more magnitude of dissipation at same time factor for almost all pressures. Initial slope of SD and PF drain indicates that their initial capacity of dissipation of pore water is faster up to 15% consolidation but thereafter its rate retard consistently, while CJ though not showing fast rate of dissipation during initial stage of consolidation but its performance is consistent and shows more degree of consolidation at less time factor. Reverse is the behavior of SW for pore pressure dissipation either at low value of time factor at high value of time factor. Comparing groups of all the isochrones of various time factor of drain materials, SW curve are distinctly showing initial concave curve.
- The micro pore structures of the SW drain and other drains are quite distinct that is initial micro porosity of SW is less compare to other drains which reflects in isochrones characteristics.

\[ SD = \text{Sand drain}, \quad SW = \text{Sandwick drain}, \quad CJ = \text{Coir-Jute fiber drain}, \quad PF = \text{Polypropylene fiber drain}, \quad n = \text{ratio of drain diameter to soil sample diameter} \]
Summary of Findings

- Other drains shows more or less same micro porosity that wise initial slope of isochorones is same to some extent, but with increase of time factor micro-porosity decreases in other drains while in CJ drain micro porosity remains almost same being the flexible nature of jute and coir fibers which helps in more dissipation of pore pressure indicating more percentage of consolidation.

*Lumped parameter ($\lambda$) vs. Degree of consolidation ($U_j$)*

- As ‘$\lambda$’ value decreases efficiency of drain material decreases. Experimental results almost match with theoretical results with $\lambda=0.2$ particularly for CJ proves to be efficient amongst other drains.

- Time-deformation curve with respect to pore pressure dissipation and settlement follow a general trend of transmission of particle orientation from one stage to another against several physico-chemical forces initially and then thereafter achieving randomly oriented or parallel oriented soil structure. The quantum of initial resistance will depend on magnitude of load, characteristics of drain material and the ‘n’ value (particularly when consolidation by radial drainage is considered) and horizontal permeability that is tortuosity in horizontal direction. The initial flocculated structure of soil bed has edge to surface or edge to edge link bonds. When load is applied some resistance is offered by this link bond. Load has to overcome the edge to edge or edge to face attraction to alter the packing geometry. During this resistance the stage can be regarded as ‘microcompressibility’, Shroff (1972) and specific deformation can be expressed as slow decay as soon as local breakdown commences, the initial resistance to compression diminishes and the rate of consolidation increases to some extent. Progressive deformation can be visualized as ‘macro compressibility’, Shroff (1972) in which deformation is caused by sliding and lifting of plate shape particles, pressing out the pore water, at the same time it loosens the ‘interfacial grip’ of adsorbed water at links of plate shape particles. Under high loading microcompressibility and interfacial grip at links of plate shape clay particle have little relevance.

II) Magnitude of consolidation
Summary of Findings

Compression index \(C_c\) vs. applied pressure

- Amongst various drain material fibers of CJ orient in such a way that the rate of dissipation remain faster in spite of pressure increase though pressure effects their orientation but compare to other drains it maintains its efficaciousness. These reflect in the value of \(C_c\) of SW and CJ which results into effective compressibility of soil.

- The \(e\) vs. \(\log p\) relationship and \(C_c\) vs. pressure indicate that because of effectiveness of CJ drain the compression index under lighter loading remains in the range of such a value that soil structure follow easy rate of dissipation showing low porosity compare to SD.

- Initial curvature portion of \(e\) vs. \(\log p\) relationship interpret soil structural resistance that is hydrodynamic lag against compressive load which giving resistance to deformation as mentioned earlier. This structural resistance or hydrodynamic lag against compression is more pronounced in SW and SD compare to PF and CJ drain. CJ or PF allows higher gradient of radial flow forming structural orientation of particle accordingly pushing the particles against face to edge bonds of random orientation bringing close to each other in a parallel orientation cultivating face to face bonds showing more shear strength of a consolidated mass. The same thing is reflected in values of compression index of the soil structure produced by various drains. In micrographs of sample collected after loading of 320kPa exhibit the same thing of above materials (put three plots of micrograph).

- For any depth the \% porosity remains less at any consolidation pressure with coir-jute drain compare to sand drain exhibiting effective consolidation.

- In general the degree of orientation(decrease of angle between particles) of particles in the soil structure undergoing consolidation indicate comparatively more face-to-face contact towards drain. Also this pattern is exhibited depth wise for any radial distance and drain material.

- In case of SD the degree of orinetation during consolidation is more near the drain (radial point r1) compare to CJ, while more degree of orientation is observed in CJ at
middle radial point r2 compare to SD, and almost same degree of orientation is observed in CJ & SD at farthest radial point r3.

- This is because of incase of SD consolidation proceeds faster near the drain thereby causing comparativley more surface settlement in that region, it could very well cause a redistribution of surface loading. While in case of CJ the condition of free strain develops which is implied that the settlement at the surface did not change the distribution of load to the soil at any location. At mid radial distance r2, the plot indicates effectiveness of CJ drain in early achievement of face-to-face orientation of particle.

**Coefficient of horizontal permeability \( (k_h) \) vs. applied pressure**

- From the above discussion it indicates that Kh value of drain increases the efficacy of rate of drainage through soil thereby it reflects coefficient of transmissivity of water through soil. For any pressure the \( k_h \) value of CJ remains efficient compare to others.

- Void ratio-pressure relationship can be of initial flocculated structure or random type of structure. The magnitude of the bonding force defining the flocculated state will control the curvature middle region. This critical region is not well defined for the random structure clay, since the bonding forces are smaller than the flocculated structure. Our is the intermediate stage of flocculated and random soil structure. The critical region is defined to some extent exhibiting some bonding forces are prevalent edge to face bonds (which is already illustrated in chapter 6 of analysis) the resistance during ‘microcompressibility’ occurring under lighter load is clearly reflected in the critical zone. Viewed microscopically, particles in a randomly oriented particles sample are rotated into more parallel orientation and then pushed closed together. These two actions probably occur simultaneously. Pushing particles closer together involves action against interparticle forces of repulsion, but particle rotation must also be considered as an integral part of compression. After critical region of curve, the fall down of curve indicate structural breakdown that occurs under consolidation pressure sufficient large to disrupt the bonds formed in the soil structure as interpreted from various plots of micrograph. The abrupt
change in slope beyond preconsolidation pressure in the latter zone of curve might be viewed as the collapse of matrix. Tortuosity with respect to actual flow path and thickness of sample works out to tend towards unity from analysis of micrographs indicating soil particles more oriented having face to face configuration.

**Shear strength**

- Comparing effect of various drain materials, the shear strength achieved at end of consolidation it is observed that CJ gains highest shear strength compare to SW, SD, PF. Soft clay consolidated by CJ gained a shear strength of 153kPa compare to shear strength gained by SW, PF, SD as 120kPa, 118kPa and 100kPa respectively. The curve of CJ lies on the top for all three radial distances while curve of SW and PF are nearly at same level indicating similar strength and curve of SD lies below the curve of PF indicating achievement of lowest shear strength.

**Influence of Drain Diameter (‘n’ value)**

I) **Rate of Consolidation (Influence of ‘n’ value keeping same material of drain and same pressure)**

**Degree of consolidation (Ur) vs. Time**

- It concludes that for 50% consolidation, \( n=11.04 \) takes 48% and 71% less time compared to \( n=16.93 \) and 21.71 for any drain material under light loading (upto 40kPa) and 53%, 63%, under constructional loading (160kPa and greater). Similarly for 80% consolidation, \( n=11.04 \) takes 35% and 61% less time compared to \( n=16.93 \) and 21.71 for any drain material under light loading and 37%, 54% under constructional loading.

- From pore pressure measurements, it infers that for 50% consolidation and mid plane radial point \( r_2, n=11.04 \) takes 59% and 76% less time compared to \( n=16.93 \) and 21.71 for any drain material under light loading and 65%, 77%, under constructional loading. Similarly for 80% consolidation, \( n=11.04 \) takes 42% and 61% less time compared to \( n=16.93 \) and 21.71 for any drain material under light loading and 51%, 67% under constructional loading.
Summary of Findings

- In case of coir-jute drain (CJ) at 50% consolidation, n=11.04 takes lowest time of 330 min & 185 min amongst other drains under light and constructional loadings respectively. Also for 80% consolidation CJ and n=11.04 remain effective exhibiting lowest time of 750 min & 550 min time under light and constructional loading respectively as discussed earlier.

- It concludes that for 50% consolidation, n=11.04 takes 135% and 300% less time compared to n=16.93 and 21.71 for any drain material under light loading and 203%, 413%, under constructional loading. Similarly for 80% consolidation, n=11.04 takes 73% and 203% less time compared to n=16.93 and 21.71 for any drain material under light loading and 86%, 225% under constructional loading.

- From pore pressure measurements, it infers that for 50% consolidation and mid plane radial point r2, n=11.04 takes 197% and 420% less time compared to n=16.93 and 21.71 for any drain material under light loading and 239%, 423%, under constructional loading. Similarly for 80% consolidation, n=11.04 takes 81% and 180% less time compared to n=16.93 and 21.71 for any drain material under light loading and 119%, 228% under constructional loading.

- For any load intensity and ‘n’ value of any drain material, the time deformation curve with respect to pore pressure dissipation remain towards the vertical axis compare to curve of settlement, that is time require for 50% or 80% consolidation is less compared to settlement curve which also reflects in isochrones curves. The curve of pore pressure for ‘n’ equal to 11.04 shifts towards vertical axis compared to ‘n’ equal to 16.93 and 21.71 for any drain material and for any pressure. While curve of pore pressure of ‘n’ equal to 16.93 align left of ‘n’ 21.71 for any drain material. The reasons for this is the specific surface area of drain which gives direct flow path to water particle for dissipation of pore water. More the specific surface area, more the discharge and higher the compressibility of soil mass. The above reason can be justified by the microporosity measured for all drains of different ‘n’ values which is presented in chapter 6.

*Coefficient of consolidation due to radial drainage (C_r)-Degree of consolidation (U_r) relationship*
Summary of Findings

- During settlement measurements it concludes that \( n = 11.04 \) for 50% consolidation shows 76% and 69% higher \( C_r \) value compare to \( n = 16.93 \) and 21.71 for any drain material under light loading and 81% and 75% under constructional loading. Similarly for 80% consolidation shows 67% and 60% higher \( C_r \) value compare to \( n = 16.93 \) and 21.71 for any drain material under light loading and 69% and 63% under constructional loading.

- During pore pressure measurements for middle radial point \( r_2 \), it concludes that \( n = 11.04 \) for 50% consolidation shows 405% and 583% higher \( C_r \) value compare to \( n = 16.93 \) and 21.71 for any drain material under light loading and 483% and 580% under constructional loading. Similarly for 80% consolidation shows 227% and 239% higher \( C_r \) value compare to \( n = 16.93 \) and 21.71 for any drain material under light loading and 290% and 298% under constructional loading.

- \( n = 16.93 \) is found to be more efficient than \( n = 21.71 \) under both light and constructional loadings. \( n = 16.93 \) shows averagely 92% higher \( C_r \) value under light loading while 60% higher under constructional loading compare to \( n = 21.71 \) but 61% lower compare to \( n = 11.04 \) under light loading and 56% lower under constructional loading.

- The general pattern of \( C_r \) vs. pressure for any ‘\( n \)’ value indicates that it increases with pressure, but at 50% consolidation variation in \( C_r \) value is higher compare to 80% consolidation. In pore pressure measurement under lighter loading there is variation in \( C_r \) value, but constancy is maintained after 50kPa for any ‘\( n \)’ value.

- For \( n = 11.04 \) the maximum value of \( C_r \) is \( 8.09 \times 10^{-4} \) cm\(^2\)/sec & \( 7.02 \times 10^{-4} \) cm\(^2\)/sec at 50% and 80% consolidation for CI from settlement consideration.

- For \( n = 16.93 \) average \( C_r \) value ranges from \( 1.46 \times 10^{-4} \) cm\(^2\)/sec & \( 3.49 \times 10^{-5} \) cm\(^2\)/sec for 80% consolidation for constructional loading from settlement and pore pressure measurements respectively.

- For \( n = 21.71 \) average \( C_r \) value ranges from \( 1.78 \times 10^{-4} \) cm\(^2\)/sec & \( 4.7 \times 10^{-5} \) cm\(^2\)/sec for 80% consolidation for constructional loading from settlement and pore pressure measurements respectively.
Summary of Findings

- Average $C_r$ value for $n=16.93$ remain in between $n=11.04$ and $n=21.71$. The lowest average value of $n=21.71$ signifies inefficiency of the drains of any material compare to drains of other ‘n’ value.

**Isochrones**

- From the consolidation ratio vs. radius of influence for various $T_r$ values reveals that sequence of consolidation for $CJ$ of $n=11.04$ at any radius of influence seems to be efficient compare to all other drains. Comparing isochrones of all three ‘n’ values it is concluded that $n=11.04$ is more effective compare to $n=16.93$ and $n=21.71$, while $n=16.93$ is more superior compare to $n=21.71$ for all drain materials.
- Trajectory of isochrones for $n=11.04$ lies above the $n=16.93$ and $n=21.71$ for both light and constructional loading. Also: trajectory of isochrones for $n=16.93$ lies above $n=21.71$ for all drain materials and loadings.

**Lumped parameter ($\lambda$) vs. Degree of consolidation ($U$)**

- As ‘$\lambda$’ value increases, drain diameter (‘n’ value) decreases. Experimental results almost match with theoretical results with $\lambda=-0.2$ particularly for $CJ$ for $n=11.04$, $\lambda=-0.19$ for $n=16.93$ and $\lambda=-0.18$ for $n=21.71$ proves to be efficient amongst other drains. From theoretical considerations $n=11.04$ proves to be efficient amongst other ‘n’ values.

II) **Magnitude of Consolidation**

**Compression index ($C_c$) vs. applied pressure**

- With the same drain $C_c$ value shows increasing trend with higher ‘n’ value. It signifies that because of low rate of dissipation in higher ‘n’ values the magnitude of compressibility increases at particular period of interval. This behavior is similar for all drains. $C_c$ value for coir-jute drain(CJ), Sandwick drain(SW), Polypropylene fiber drain(PF), Sand drain(SD) for $n=11.04$ are 0.272, 0.279, 0.292, and 0.312 respectively.
- Amongst the various ‘n’ values the $n$ equal to 11.04 provides optimum specific surface area to the saturated surrounding soil structure for a given diameter of
influence zone of soil mass. Because of this gradient of radial flow during consolidation can help producing low level of structural resistance to compression in this case compare to other ‘n’ value of 16.93 and 21.71. The load component during higher level of loads can help structural breakdown or pushing the particles at a more rate leading to final consolidated mass at 320kPa. It is reflected in micro porosity, degree of orientation and tortuosity measurement graphs drawn for the final load.

**Coefficient of horizontal permeability \((k_h)\) vs. applied pressure**

- The horizontal permeability \((k_{h30})\) obtained by settlement decreases with increase in the pressure for almost all drains and for all ‘n’ values.
- From settlement analysis it concludes that \(n=11.04\) for 50% consolidation shows 278% and 289% higher \(k_h\) value compare to \(n=16.93\) and 21.71 for any drain material under light loading and 735% and 3025% under constructional loading. Similarly for 80% consolidation shows 190% and 200% higher \(k_h\) value compare to \(n=16.93\) and 21.71 for any drain material under light loading and 442% and 1862% under constructional loading.
- From pore analysis for middle radius point \(r_2\) it concludes that \(n=11.04\) for 50% consolidation shows 305% and 373% higher \(k_h\) value compare to \(n=16.93\) and 21.71 for any drain material under light loading and 732% and 2747% under constructional loading. Similarly for 80% consolidation shows 165% and 134% higher \(k_h\) value compare to \(n=16.93\) and 21.71 for any drain material under light loading and 454% and 1460% under constructional loading.
- \(n=16.93\) shows more coefficient of transmissivity of pore water then \(n=21.71\) under both light and constructional loadings.
- From settlement analysis \(n=16.93\) shows averagely 47% and 512% higher \(k_h\) value under light loading and constructional loading compare to \(n=21.71\) but 37% and 77% lower compare to \(n=11.04\) under light loading and constructional loading for 50% consolidation under any drain material.
Summary of Findings

• From pore pressure analysis n=16.93 shows averagely 63% and 411% higher $k_h$ value under light loading and constructional loading compare to n=21.71 but 45% and 73% lower compare to n=11.04 under light loading and constructional loading for 50% consolidation under any drain material.

• From pore pressure analysis for 50% consolidation it concludes that $k_h$ value of mid plane pore pressure for CJ works out to be 76% and 146% higher under light loading and constructional loading compare to PF for any ‘n’ value while for 80% consolidation CJ shows 33% and 77% higher value under light loading and constructional loading respectively.

Shear strength

• Gain in shear strength was observed for all three ‘n’ values for any drain material after consolidation, but highest gain was observed in case of ‘n’ equal to 11.04 for any drain material. Average post shear strength increased to 150kPa from pre shear strength of 15kPa.

• Shear strength increases as ‘n’ value decreases (drain diameter increases) for any drain material. Comparing effect of various ‘n’ values for CJ drain, the shear strength achieved at end of consolidation is highest for ‘n’ equal to 11.04 compare to 16.93 and 21.71. The shear strength achieved for n’ equal to 11.04, 16.93 and 21.71 is 153kPa, 129kPa, and 109kPa respectively. Also more shear strength is observed for nearest radial point and this effect is true for any ‘n’ value. The curve of 11.04 lies above the curve of ‘n’16.93 and ‘n’21.71 for any drain material. Lowest gain in shear strength is observed in case of SD compare to CJ, SW, PF, while almost low strength is observed in case of ‘n’21.71 for all drain materials. In general ‘n’ equal 11.04 provides more specific surface area being larger diameter of the particle which facilitate easy and more dissipation of pore water pressure under particular load thereby bringing the particle close together in a parallel orientation in more number.

Influence of Geometry (shape) of Drain

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I) Rate of Consolidation

Degree of consolidation (Ur) vs. Time

- Considering settlement measurement it concludes that for 50% consolidation, CSSD of n=11.04 takes 41% less time compared to any drain material under light loading and 48%, under constructional loading. Similarly for 80% consolidation, CSSD takes 39% less time compared to any drain material under light loading and 36% under constructional loading.

- From pore pressure measurements, it infers that for 50% consolidation and mid plane radial point \( r_c \), CSSD of n=11.04 takes 13% less time compared to other drain shapes under light loading and 20% under constructional loading. Similarly for 80% consolidation, CSSD takes 15% less time compared to other drain shapes under light loading and 18% under constructional loading.

- CSSD of n=11.04 takes lowest time in compare to BSSD, PSSD, TSSD both under light and constructional loading. However BSSD for 50% consolidation takes 12% & 23% lower time in compare to PSSD & TSSD but 50% higher in compare to CSSD under light loading. Also PSSD takes 13% lower time compare to TSSD but 70% higher in compare to CSSD. Similarly BSSD for 80% consolidation takes 12% & 12% lower time in compare to PSSD & TSSD but 53% higher in compare to CSSD under light loading. Also PSSD takes equal time compare to TSSD but 73% higher in compare to CSSD.

- For any load intensity and for any geometry of sand drain with ‘n’ value equal to 11.04, the time deformation curve with respect to pore pressure dissipation remain towards the vertical axis compare to curve of settlement, that is time require for 50% or 80% consolidation is less compare to settlement curve which also reflects in isochrones curves.

- Though from the point of rate of dissipation of pore pressure for a circular shape drain seems to be efficient, the band shape drain provide best construction facility during installation in terms of cost and speed of work.

CSSD= Circular shape sand drain, PSSD = Plus shape sand drain
BSSD = Band shape sand drain, TSSD = Triod shape sand drain
Summary of Findings

- Based on the equivalent diameter concept the dimensions of various shapes of drain are worked out. Though surface area of plus shape and tripod shape drain work out to be higher then band shape and circular shape drain, the draining efficiency of circular and band shape is higher then other two shapes of drain. It may be due to right and acute angles of the drain which intercept the path of flow of water to some extent.

- Under compressional stresses the drain-clay interface are not remaining compatible with the deform shape of the drain, therefore the higher surface area of plus and tripod shape drain are not remaining advantageous for the easy flow of water from the central drain.

- For any load intensity and for any geometry of sand drain with ‘n’ value equal to 11.04, the time deformation curve with respect to pore pressure dissipation remain towards the vertical axis compare to curve of settlement, that is time require for 50% or 80% consolidation is less compare to settlement curve which also reflects in isochrones curves. The curve of pore pressure for CSSD shift towards vertical axis compare to BSSD, PSSD and TSSD for any pressure for same specific surface area. The curve of CSSD remain towards vertical axis showing less time for 50% consolidation thereafter all curves merge to some extent. The curve of BSSD remains towards vertical axis more compare to curve of BSSD and TSSD for both pore pressure and settlement measurements. The above observation may be due to higher hindrance for the conductivity of the radial flow to the drain compare to other drains wise band, tripod and plus shape. This is in similitude with flow per unit time through various shaped notch under constant head. That is circular notch gives higher discharge compare to rectangular notch, plus shape notch and tripod shape notch. The hydraulic conductivity will always remain uniform through circular one, least quantum of vortex is observed in circular one compare to other shape notch. To some extent this is true for flow through different shape drain with a different hydraulic mean radius of capillary formed.

CSSD = Circular shape sand drain, PSSD = Plus shape sand drain
BSSD = Band shape sand drain, TSSD = Tripod shape sand drain
**Summary of Findings**

**Coefficient of consolidation due to radial drainage ($C_r$)-Degree of consolidation ($U_r$) relationship**

- From settlement analysis it concludes that CSSD of $n=11.04$ for 50% consolidation shows 71% higher $C_r$ value compare to other geometry of drains under light loading and 96% under constructional loading. Similarly for 80% consolidation shows 65% higher $C_r$ value compare to other geometry of drains under light loading and 57% under constructional loading.

- From pore pressure analysis for middle radial point $r_2$ it concludes that $n=11.04$ for 50% consolidation shows 12% higher $C_r$ value compare to other geometry of drains under light loading and 21% under constructional loading. Similarly for 80% consolidation shows 14% higher $C_r$ value compare to other geometry of drains under light loading and 18% under constructional loading.

**Coefficient of consolidation due to radial drainage ($C_r$) vs. applied pressure**

- The general pattern of $C_r$ vs. pressure for any shape of drain indicates that it increases with pressure, but at 50% consolidation variation in $C_r$ value is higher compare to 80% consolidation. In pore pressure measurement under lighter loading there is variation in $C_r$ value, but constancy is maintained after 50kPa for any shape of drain.

- Average $C_r$ value for BSSD remain in between CSSD and PSSD. The lowest average value of TSSD signifies inefficiency of the drain geometry compare to geometry of other drains.

**Isochrones**

- From the consolidation ratio vs. radius of influence for various $T_r$ values reveals that sequence of consolidation for CSSD of $n=11.04$ at any radius of influence seems to be effective compare to other geometry of drains. Comparing isochrones of all four shapes it is concluded that CSSD is more effective compare to others, while BSSD is superior compare to PSSD & TSSD for same drain material. Trajectory of isochrones
for CSSD lies above the BSSD, PSSD, TSSD for both light and constructional loading. Overall TSSD is in-effective in increasing rate of compressibility and dissipation of pore water pressure.

*Lumped parameter (λ) vs. Degree of consolidation (Uj)*

- Experimental results almost match with theoretical results with $\lambda = -0.125$ particularly for CSSD, $\lambda = -0.12$ for BSSD, $\lambda = -0.11$ for PSSD and $\lambda = -0.1$ for TSSD proves to be efficient amongst other drains. From the above analysis it can be said that Circular shape is more efficient in compare to other shapes in accelerating rate of consolidation.

II) **Magnitude of Consolidation (e vs. log P)**

*Compression index (C_c) vs. applied pressure*

- It is observed that for CSSD lower $C_c$ value is obtained compared to other geometry of sand drains. It signifies that because of low rate of dissipation in other shapes of drains the magnitude of compressibility increases at particular period of interval. This behavior is similar for all drains. $C_c$ value for CSSD, BSSD, PSSD, and TSSD for $n=11.04$ are 0.161, 0.241, 0.271, and 0.282 respectively. Under no geodrain condition the value of $C_c$ is 0.42.
- There is no much variation of Compression index with shape of drain, though the rate of drainage for a particular static loading seems to be faster in CSSD compared to others.
- Circular shape sand drain experience least interference of dissipation of radial flow compare to band drain, tripod shape and plus shape drain. This more and easy dissipation of pore pressure is because of the higher gradient of water flow through soil structure which has been cultivated under the load. Under lighter load because of the structural resistance it shows convex upward curve while after critical zone the particle orientation leading to parallel alignment exhibit higher slope of the curve (e vs. log P) tending to final consolidated soil mass having face to face bond.

CSSD= Circular shape sand drain, PSSD = Plus shape sand drain
Summary of Findings

BSSD = Band shape sand drain, TSSD = Triod shape sand drain

Coefficient of horizontal permeability ($k_h$) vs. applied pressure

- From settlement analysis it concludes that $n=11.04$ for 50% consolidation shows 274% higher $k_h$ value compare to any shape of sand drain under light loading and 36% under constructional loading. Similarly for 80% consolidation shows 259% higher $k_h$ value compare to any shape of sand drain under light loading and 9% under constructional loading.

- From pore pressure analysis for mid plane radial point $r_2$ it concludes that CSD of $n=11.04$ for 50% consolidation shows 143% higher $k_h$ value compare to any shape of sand drain under light loading and 15% lower under constructional loading. Similarly for 80% consolidation it shows 149% higher $k_h$ value under light loading and 18% lower under constructional loading.

Shear Strength

- More gain in shear strength is observed in case of CSSD compare to PSSD, BSSD and TSSD for same ‘n’ value and same specific surface area. The shear strength observed in case of CSSD, PSSD, BSSD, and TSSD in terms of magnitude is 96kPa, 90kPa, 86kPa and 82kPa respectively. The shear strength increases towards the drain for all shapes of drain. Sample having CSSD have marked strength compare to others. The strength is 1.07, 1.12, and 1.17 times higher compared to PSSD, BSSD and TSSD. The reasoning for the above is as follows. Though all the drains have same specific surface area, the radial flow towards the drain experience hindrances in PSSD, TSSD and BSSD. BSSD has good versatility in the installation process but dissemination of pore pressure through BSSD takes more time and structure of soil produced may not be well oriented with face-to-face contact. Same is the story with other drains, then circular one. CSSD controls rate as well as magnitude of the pore pressure dissipation in achieving required strength.

Dynamic Analysis of Consolidated Clay Bed by Central Vertical Geodrain
Post vane shear strength of reinforced consolidated clay mass before application of seismic stresses

For sandwich of n= 16.93 the results of vane shear strength indicates that strength increases from 14.6kpa to maximum of 113.7kpa i.e. 88% increment. It was also observed that strength is more towards the first radial point r₁ while it is less at r₃ i.e. 101.5kpa. But generally for analysis the mid radial point (r₂) is consider in design. For n=21.71 the strength increased from 12.1kpa to 99.1kpa i.e. 87% increment without application of seismic stresses. In this case also the strength was maximum at r₁ while it was minimum at r₃ i.e. 97.4kpa. This results indicates that as the diameter of drain increases the soil shear strength also increases.

In brief, before consolidation of the soil sample, the same strength (12.5kPa) for any radial distance is observed for all the ‘n’ value. The strength of consolidated soil mass at the end of 320kPa load intensity exhibit 9 times strength than 10kPa for n=16.93, while for n=21.71 it is about 7.5 times. The strength at mid radial point is less than the strength nearer at drain and more than farthest radial point r₃.

Post vane shear strength of reinforced consolidated clay mass after application of seismic stresses

Under dynamic analysis, SW of n=16.93, the vane shear strength indicates that the % loss in strength is more during first or initial vibration, afterwards the loss in strength is more or less constant. The average strength for n=16.93 decreased from 108.53kpa to 51.10kpa i.e. 53% decrement for vibration period of 5 seconds. While for n=21.71 the average strength decreased from 99.0kpa to 46.3kpa i.e. 53% decrement. Initial earthquake shock (period of vibration equal to 5 sec) is sufficient to cause metastable condition in card house structure of soft clay for any ‘n’ value but smaller the ‘n’ value more resistance is offered against strength loss. In any n=16.93 the % strength loss(46%) is less then n=21.71. Percentage loss in strength for any period of vibration is less in smaller ‘n’ value compare to higher ‘n’ value 11.04.
Summary of Findings

- For n=16.93 under seismic stresses the results of vane shear strength for seismic period of 15 secs, 30 secs, 60 secs and 120 secs indicates that %loss in strength is 46% averagely remains constant though seismic periods was increased while if we consider the net effect in strength then it is only 6 to 8%which may be an indication of particle rearrangement or the card house structure of soft clay to have became horizontal whose metastability was not affected by adsorbed water at later stages to some extent. While or n=21.71 the % loss in strength was averagely 68%which is much higher compare to n=16.93values.Also it was observed that there was no change in in-situ placed condition of sandwich or even no settlement of only sandwich was observed nor any change in its diameter was observed indicating sandwich as a stable drain under seismic conditions which prevents the soft soil to get quick.

- Initial earthquake shock (period of vbration equal to 5 sec) is sufficient to cause metastable condition in card house structure of soft clay for any ‘n’ value but smaller the ‘n’ value more resistance is offered against strength loss. In any n=16.93 the % strength loss(46%) is less then n=21.71.Percentage loss in strength for any period of vibration is less in smaller ‘r’ value compare to higher ‘n’ value 11.04.

Influence of Water Content Ratio (WCR)

- As water content ratio increases the value of Cc increases for any drain material and for same ‘n’ value. For same water content ratio the variation in compression index (Cc) value for different drain material ndicate 0.556 for coir-jute drain (CJ), 0.546 for sandwich drain (SW), 0.538 for polypropylene fiber drain (PF) and 0.532 for sand drain (SD). From the pattern of variation it infers that for same Cc value the WCR remains in the ascending order of CJ, SD, PF and SW. For same WCR, the Cc values are descending order of CJ, SW, PF and SD.

- Coir-jute drain show lowest water content at the end of any load amongs various drains proving its ability to consolidate soil more compare to others.

Influence of Consolidation Pressure Ratio (CPR)
Summary of Findings

- As CPR value increases the compression index (Cc) value increases for any drain material. In the higher range of CPR value, the Cc value is in the order of CJ, SW, PF and SD while for lower range of same CPR value the sequence is in the order of CJ, SW, SD and PF.

- As CPR increases $k_v$ and $k_h$ increases for any drain material and therefore the ratio $k_h/k_v$ increases as CPR increases for any drain material. Among various drains, CJ gives highest $k_h/k_v$ of the order of 27 which indicates CJ drain facilitates more gradient of water towards drain forming displacement of particles in such a way that horizontal permeability of soil increases leading ratio more for end of any load.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) along with the quanti-image analyzer with system of MIC (micro-structure characterization) software has been employed to deduce the interpretation by this nano technology, which will give the relative compression of circular soil sample from extreme radial distance to interface of drain with soil.

Influence of micro-porosity

- From nano analysis of micrograph, it interprets that for same height level of sample the percentage micro pores are increasing from central drain radially to outer radial point. Between nearest radial point $r_1$ and clay-drain interface the percentage decrease of micro pore is more compared to mid plane radial point $r_2$ and outward radial point $r_3$. Because of faster rate of dissipation the achieved void ratio or porosity which is worked out is less in case of coir-jute drain compare to sand drain.

- Though, the micro pore distribution at interface(drain-soil) at any level (height) is less compare to $r_1$, $r_2$ and $r_3$, in general the distribution of the micro-porosity exhibit higher magnitude of consolidation with increase of depth at any radial point however, it has been confirmed this observation at mid plane radial point $r_2$. In general the degree of orientation(decrease of angle between particles) of particles in the soil structure undergoing consolidation indicate comparatively more face-to-face contact towards drain. Also this pattern is exhibited depth wise for any radial distance and drain material.
Influence of angle of orientation

- The software measurement for angle of angularity of one particle with other of various micrographs indicates that orientation of particle becomes more or less face to face to some extent as we approach towards drain from extreme radial point.

- In case of SD the degree of orientation during consolidation is more near the drain (radial point r1) compared to CJ, while more degree of orientation is observed in CJ at middle radial point r2 compared to SD, and almost same degree of orientation is observed in CJ & SD at farthest radial point r3.

Influence of Tortuosity

- Tortuosity is a real measure of actual flow path towards radial direction towards central drain during consolidation process. Tortuosity tends to unity in case of CJ drain compared to SD as mentioned earlier. Soil structure because of the gradient of flow in horizontal direction and vertical load help causes more quantum of face-to-face contact in the former case. For the same drain the depth wise tortuosity also indicate the effect of over burden to some extent. In case of coir-jute drain the tortuosity at interface and at mid radial point are almost same indicating uniform surface settlement unlike sand drain.

The theoretical relationship obtained between average degree of consolidation versus time factor for various values of \( \lambda \) both for positive and negative range fits well with the experimental results obtained from the laboratory studies. The above findings will give definitely provide a ready solution to the design engineers and field persons in making the selection of effective drain material, optimum drain diameter(size) and easy workable drain geometry with respect to site conditions. The appropriate value of lumped parameter \( \lambda \) will directly give the clue to design engineer regarding the selection of prefabricated vertical geodrain with respect to field conditions.