International Journal of Civil Engineering and Technology (IJCIET)
Volume 11, Issue 2, February 2020, pp. 31-42, Article ID: IJCIET_11_02_004
Available online at http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=11&IType=2
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

COMPRESSIBILITY BEHAVIOUR OF COMPACTED SOILS – HYPERBOLIC MODELLING

U. Venkata Ratnam
Research Scholar, Department of Civil Engineering,
SVU College of Engineering, Tirupati, AP, India

K. Nagendra Prasad
Professor, Department of Civil Engineering,
SVU College of Engineering, Tirupati, AP, India

ABSTRACT

Compacted soils constitute most engineering projects such as earth dams, embankments, pavements, and engineered slopes because of their high shear strength and low compressibility. The compressibility behavior of compacted soils is a key soil parameter in the design of earth structures but it is not determined correctly owing to partly saturated state. The compressibility of compacted soils can be better evaluated under the framework of hyperbolic behavior. One dimensional Consolidation tests on compacted specimens were conducted using conventional oedometer apparatus under constant water content condition. Tests were conducted by compact the soil specimens at respective optimum moisture contents for eight different soil samples, of varying grain size characteristics and consistency limits, collected from Tirupati Region. The main objective of this study is to examine the compressibility behavior of compacted soils to propose a phenomenological model. It is observed that the compressibility behavior can be captured by hyperbolic modeling with model parameters involved in the behavior being initial void ratio, $e_{0,}$ *representing the initial state of soil and other hyperbolic constants linked to this state. The data of 6 samples were used for developing the model and the data of remaining two samples were used for predicting the observed response from the model proposed. The data of published literature has also been used to predict the experimental behavior to bring out the merits of the model proposed.*

Keywords: compacted soils, analysis and prediction, compressibility behaviour, hyperbolic model.

Cite this Article: U. Venkata Ratnam and K. Nagendra Prasad, Compressibility Behaviour of Compacted Soils – Hyperbolic Modelling. *International Journal of Civil Engineering and Technology,* 11(2), 2020, 31-42.

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=11&IType=2

1. INTRODUCTION

The study of unsaturated soils has a long but somewhat uneven history (Gens et al, 2006) [3]. Unsaturated soils tended to be lumped together with other materials in soil categories variously described as ‘‘difficult soils’’, ‘‘regional soils’’, ‘‘special soils’’ or other similar names (Sam Bulolo and Eng Choon Leong, 2019) [14].

2. BACKGROUND INFORMATION

Compacted soils constitute most engineering projects such as earth dams, embankments, pavements, and engineered slopes because of their high pre-compression stresses and shear strength. The shear strength of compacted soils is a key soil property in the design of earth structures but it is seldom determined correctly due to their unsaturated state. Research shows that there exists a close relationship between the soil-moisture state and shear strength of unsaturated soils (Burland and Jennings, 1962, Fredlund et al., 1978, Vanapalli et al., 1998 and Matsushi and Matsukura, 2006) [12, 2, 15, and 13]. The study of shear strength behaviour of compacted soils is well documented (Venkata Rathnam and Nagendra Prasad, 2019) [16] whereas the compressibility behaviour has to be still explored for proposing a framework, by which the behaviour can be easily predicted.

3. MATERIALS AND METHODS

The soil samples from eight different locations were brought to laboratory after removing the top filled up soil. The soils are brought to the laboratory for further processing. The soil samples were air dried and sieved through 20mm sieve and the fraction passing through the 20mm sieve has been used for conducting the experimental study. The experimental investigation considers soil samples from eight different locations of Tirupati Region. The soils are classified as Clayey Sand (SC) to Clay with High Compressibility (CH). The fine fraction ranges from 37-88%. The Liquid Limit values range from 30% to 80% and the Plasticity Index ranges from 8% to 60%. The properties represent inherent variability though categorized into similar broad classification as per IS 1498-1970 [4]. The soils are of this type are typical of the soils encountered in the region. The soils tested cover wide spectrum of soil variety and the experimental results on these soils provide basis for analyzing and predicting the soil behaviour as any soil found locally would fall into one of these categories.

Laboratory tests were carried out as follows:

(a) To determine Physical Properties of Soil {Classification}:

- Consistency limit tests [Atterberg]
- Particle size analysis

(b) To determine Mechanical Properties of Soils:

- Compaction,
- OedometerCompression

All tests were performed as per bureau of Indian Standard Specifications as mentioned in the Table 1.

Table 1 Tests Conducted

Test Conducted	IS code of Practice
Grain size Distribution	IS 2720-4:1985
Liquid Limit	IS 2720-5:1985
Plastic Limit	
Specific Gravity	IS : 2720 (Part III/Sec 1-1980
Free Swell Index	IS 2720-40:1985
Maximum Dry Density	IS 2720-7:1980
Optimum Moisture Content	
Oedometer Test	IS: 2720 (Part. XV) 1986

The Basic properties of the soils are presented in Table 2

3.1. Grain Size Distribution

Each soil sample received from the field was prepared as specified in IS :2720 (Part 1)-1983 [5]The soil fractions passing 20mm IS Sieve was taken separately for the analysis. The soaked soil specimen was washed on the 75-micron IS Sieve until the water passing the sieve is substantially clean. The fraction retained on the sieve was tipped without loss of material in a try, dried in the oven, and sieved through the nest of sieves with the sieve sizes specified in 4.1.2 of IS 2720-4:1985 [8] : 2mm, 425μ, and 75μ, by hand . The fraction retained on each sieve should be weighed separately and the masses recorded. The cumulative mass of soil fraction retained on each sieve was calculated. The percentage of soil fraction retained on each sieve was calculated on the basis of the mass of the sample passing 4’75-mm IS Sieve taken for the initial analysis. The combined gradation on the basis of the total soil sample taken for analysis shall then be calculated. The test results are presented in Figure 1. It may be observed from the results that the grain size distribution is quite varying though the samples come under similar classification as per IS 1498-1970 [4]. These characteristic features are typical of soil samples encountered in the region.

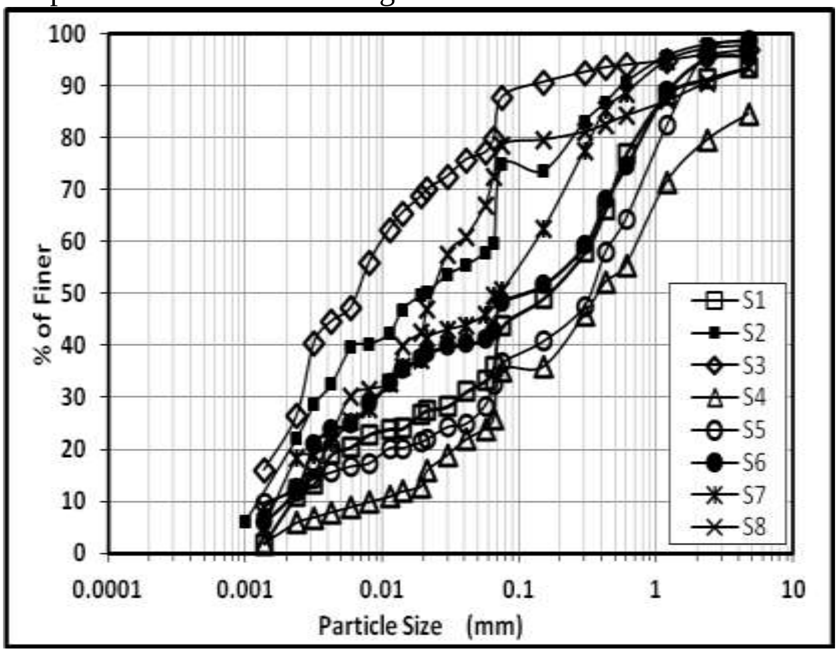

Figure 1 Grain size distribution for the samples Tested

3.2. Consistency Limits

The liquid and plastic limits of soils are both dependent on the amount and type of clay in a soil and form the basis for the soil classification system for cohesive soils based on the plasticity tests. Besides their use for identification, the plasticity tests give information concerning the cohesion properties of soil and the amount of capillary water which it can hold. They are also used directly in specifications for controlling soil for use in fill. These index properties of soil have also been related to various other properties of the soil.

3.2.1. Liquid Limit

A sample weighing about 120 g was taken from the thoroughly mixed portion of material passing 425-micron IS Sieve. About 120 g of the soil sample passing 425-micron IS Sieve was mixed thoroughly with distilled water in the evaporating dish. A portion of the paste was placed in the cup above the spot where the cup rests on the base, squeezed down and spread into position. The cup was fitted and dropped by turning the crank at the rate of two revolutions per second until the two halves of the soil cake come in contact with bottom of the groove along a distance of about 12 mm. This length shall be measured with the end of the grooving tool or a ruler. The number of drops required to cause the groove close for the length of 12 mm shall be recorded. A flow curve was plotted on a semi-logarithmic graph representing water content on the arithmetical scale and the number of drops on the logarithmic scale. The flow curve is a straight line drawn as nearly as possible through the four or more plotted points. The moisture content corresponding to 25 drops as read from the curve shall be rounded off to the nearest whole number and reported as the liquid limit of the soil (IS 2720-Part 5-1985) [10].

3.2.2. Plastic Limit

The soil sample was mixed thoroughly with distilled water on the flat glass plate till the soil mass becomes plastic enough to be easily molded with fingers. A ball was formed with about 8 g of this plastic soil mass and rolled between the fingers and the glass plate with just sufficient pressure to roll the mass into a thread of uniform diameter throughout its length. The rate of rolling would be between 80 and 90 strokes/min counting a stroke as one complete motion of the hand forward and back to the starting position again. The rolling was done till the threads are of 3 mm diameter. The soil was then be kneaded together to a uniform mass and rolled again. This process of alternate rolling and kneading was continued until the thread crumbled under the pressure required for rolling and the soil can *no* longer be rolled into a thread. The crumbling may occur when the thread has a diameter greater than 3 mm. The moisture content corresponding to this state was recorded as plastic limit (IS 2720-Part 5-1985) [10].

3.3. Specific Gravity

Specific gravity of soils finds application in finding out the degree of saturation and unit weight of moist soils. The unit weights are needed in pressure, settlement and stability problems in soil engineering (IS :2720 (Part III/Sec 1-1980) [7].

The complete density bottle with stopper shall be dried at 105 to 110^{0}C, cooled in the desiccator and weighed to the nearest 0.001 g (m_1). The 50 g sample was if necessary be ground to pass a 2-mm IS test sieve. A 5 to 10 g sample was be obtained by riffling, and oven dried at 105 to 110°C .This sample was transferred to the density bottle direct from the desiccators in which it has been cooled. The bottle and contents together with the stopper shall be weighed to the nearest 0.001 g (m_2). The bottle and contents was added further with air-free liquid until the bottle was full (m_3). The bottle was then be cleaned out and filled completely with air free liquid (m_4)

The specific gravity of the soil particles G was calculated using the following equation:

$$G = \frac{m_2 - m_1}{(m_2 - m_1) - (m_3 - m_4)}$$

3.4. Free Swell Index

Free swell is the increase in volume of a soil, without any external constraints, on submergence in water. The possibility of damage to structures due to swelling of expensive clays need be identified, at the outset, by an investigation of those soils likely to possess undesirable expansion characteristics (IS 2720-40:1985) [9].

Each soil specimen was poured in each of the two glass graduated cylinders of 100 ml capacity. One cylinder was be filled with kerosene oil and the other with distilled water up to the 100 ml mark. After removal of entrapped air by gentle shaking or stirring with a glass rod, the soils in both the cylinders shall be allowed to settle. Sufficient time (not less than 24 h) was being allowed for the soil sample to attain equilibrium state of volume without any further change in the volume of the soils. The final volume of soils in each of the cylinders was read out.

The level of the soil in the kerosene graduated cylinder would read as the original volume of the soil samples, kerosene being a non-polar liquid does not cause swelling of the soil. The level of the soil in the distilled water cylinder was read as the free swell level. The free swell index of the soil shall be calculated as follows:

$$\text{Free swell index, percent} = \frac{V_d - V_k}{V_k} \text{ where}$$

V_d= the volume of soil specimen read from the graduated cylinder containing distilled water, and

V_k = the volume of soil specimen read from the graduated cylinder containing kerosene.

3.5. Compaction Characteristics

The purpose of a laboratory compaction test is to determine the proper amount of mixing water to be used, when compacting the soil in the field and the resulting degree of denseness which can be expected from compaction at optimum moisture content. To accomplish this, a laboratory test which will give a degree of compaction comparable to that obtained by the field method used is necessary. This procedure is satisfactory for cohesive soils but does not lend itself well to the study of the compaction characteristics of clean sands or gravels which displace easily when struck with the rammer (IS : 2720 (Part VII) – 1980) [11].

A representative portion of air dried soil material and large enough to provide about 6 kg of material passing at 20-mm IS sieve A 5-kg sample of air dried soil passing the 19 mm IS test sieve was taken .The sample was mixed thoroughly with a suitable amount of water depending on the soil type . The mould, with base plate attached, was weighed to the nearest 1 g (m1). The mould was placed on a solid base, such as a concrete floor and the moist soil was compacted into the mould, with the extension attached, in three layers of approximately equal mass, each layer being given 25 blows from the 2.6-kg rammer dropped from a height of 310 mm above the soil. The blows were distributed uniformly over the surface of each layer. The rammer always falls freely. The amount of soil used was sufficient to fill the mould, leaving not more than about 6 mm to be struck off when the extension is removed. The extension shall be removed and the compacted soil shall be leveled off carefully to the top of the mould by means of the straightedge. The mould and soil shall then be weighed to 1 g (m2). The compacted soil specimen was removed from the mould and placed on the mixing tray. The water content of a representative sample of the specimen was determined. The remainder of the soil specimen was broken up, rubbed through the 19-mm IS test sieve, and then mixed with the remainder of the original sample. Suitable increments of water was added successively and mixed into the sample, and the above procedures from operations wererepeated for each increment of water added. The total numbers of determinations made were least five, and the range of moisture contents should be such that the optimum moisture content, at which the maximum dry density occurs, is within that range.

Compaction test (standard proctor test) was performed to determine the optimum moisture contents and dry densities of the soil samples. For the determination of the OMC a series of soil mixes were prepared over a range of moisture contents. When the dry density was plotted against the respective moisture content, all eight samples produced typical moisture-density curves with clearly identifiable optimums, as shown in Figure 2. A glimpse of all the test results comprising of basic properties is provided in Table 2.

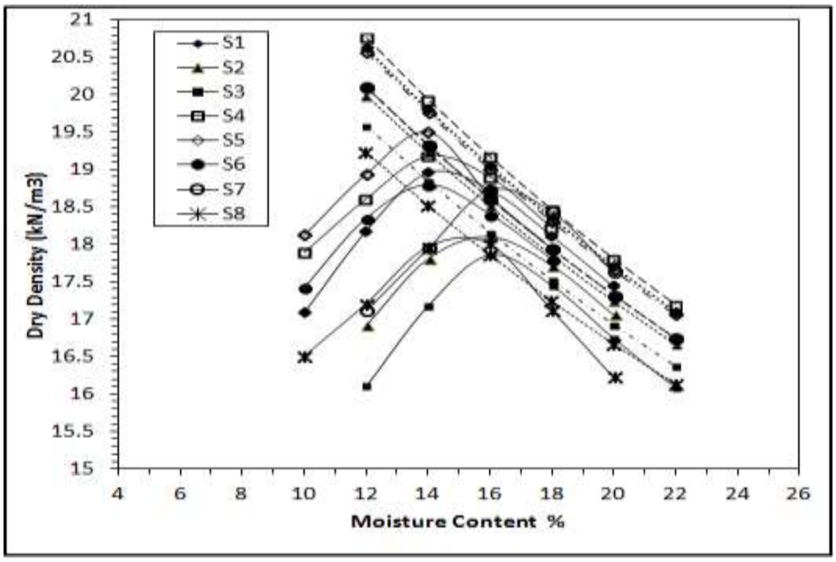

Figure 2 Compaction test results for the soil samples tested

The behaviour of compacted soils under compression and under shear is being analysed to propose a framework for describing the constitutive Behaviour of Compacted soils.

Table 2 Basic properties

S.No	Properties	S1	S2	S3	S4	S5	S6	S7	S8
1	Specific Gravity	2.74	2.63	2.56	2.76	2.73	2.65	2.65	2.5
	Gravel (%)	9.20	1.20	3	21.16	1.20	4.20	2.22	6.41
	Sand (%)	47.00	24.00	19	43.47	62.10	47.40	47.17	14.90
2	Silt (%)	37.42	34.31	21.49	20.46	24.49	30.75	32.26	65.91
	Clay (%)	6.38	40.49	56.51	14.91	12.21	17.65	18.34	12.78
	% Passing 425 □	66.2	86.74	93.51	52.25	58	68	85.43	82.62
	Liquid Limit (%)	62.00	41.50	51.00	32.50	81.50	65.50	60.00	55.00
3	Plastic Limit (%)	27.00	21.00	19.00	24.60	21.00	19.00	16.27	17.00
	Plasticity Index (%)	35.00	20.50	32.00	7.90	60.50	46.50	43.73	38.00
4	IS Classification 1498-1970)	SC	CI	CH	SM	SC	SC	SC	CH
5	Free Swell Index,%	110	108	105	60	182	160	135	110
6	Maximum Dry Density,kN/m^3	19.00	18.12	17.90	19.22	19.50	18.80	18.75	18.10
7	Optimum Moisture content,%	15.00	17.00	16.50	14.50	14.00	14.50	15.50	16.90

3.6. Oedometer Test

After compacting the soil sample at optimum moisture content obtained as per IS 2720-Part 7 [11], the consolidation ring shall be gradually inserted into the sample by pressing with hands and carefully removing the material and the ring. The consolidometer shall be placed in position in the loading device and suitably adjusted. The dial gauge is then clamped into position for recording the relative movement between the base of the consolidation cell and the loading cap. The consolidation cell has been filled with water. A seating pressure of 0.05 kg/cm^2 shall be applied to the specimen. For consolidation testing, it is generally desirable that the applied pressure at any loading stage be double than that at the preceding stage. Accordingly, the test has been conducted applying monotonic loading.

4. ANALYSIS OF TEST RESULTS

The aim of the present paper is to bring out a step wise procedure to assess the compressibility behaviour of compacted soils. Accordingly the soil samples considered in the present investigations were subjected to monotonic loading. The test results are presented in Figures 3-4. The Figure 3 represents the e-σv relationship whereas the figure 4 represents the e-log σv relationship. It may be observed (Figure 4) that the compressibility behaviour is characterised by non linear response characterising the yield stress. Pressure at which the stiffness of the soil in the oedometer falls rapidly and slope of the e-logσv curve shows a sudden change characterised by a breaking point, is termed as yield stress. The compression is negligible before yield stress followed by relatively high compressibility is seen up to very higher level of stress.

An attempt has been made to re-plot the behaviour on transformed platform with (e_0-e) on Y- axis and σ_v/p_a on X-axis , as shown in Figure 5, pa being atmospheric pressure. It may be seen that the response is quite akin to hyperbolic response. The similar trends are observed for all the soil samples tested.

In order to further reinforce the hyperbolic nature of response the test results are plotted on transformed plot with $\frac{\sigma_v / p_a}{(e_0 - e)}$ on Y-axis and σ_v / p_a on X-Axis. It may be observed, from the Figure 6 that the response is straight line of the form, equation 1

$$\frac{\sigma_v / p_a}{(e_0 - e)} = a1 + b1\left(\frac{\sigma_v}{p_a}\right) \qquad (1)$$

Where a1 and b1 are hyperbolic parameters

Having noticed that the compressibility behaviour of compacted soils to be in conformity with hyperbolic nature, as shown in Figure 6 and equation 1, an attempt has been made to find out the dependency of hyperbolic parameters a1 and b1 with initial state of the soil. It is broadly observed that the compressibility behaviour of compacted soils begin with void ratio corresponding to the initial state of compaction and shows rigid response initially followed by relatively more deformations after reaching a particular stress which is usually defined as yield stress. Since the compression behaviour is dependent on state of the soil at which loading begins, it has been investigated to examine the dependency of the parameters a1 and b1 with respective initial void ratios.

It shown in Figure 7 that the parameters a1 is proportionately dependent on initial void ratio as given by the equation as shown below

$$a1 = 18.42\,(e_o) + 7.342 \text{ with } R^2 = 0.975 \qquad (2)$$

Similarly, the parameter b1 is dependent on initial void ratio as given by the following expression

$$b1 = 3.301\,(e_o) + 2.837 \text{ with } R^2 = 0.958 \qquad (3)$$

It may be noted that the above correlations are quite high indicating the dependency of hyperbolic parameters a1, b1 on initial void ratios. .

5. MODEL PREDICTIONS

In the development of the expressions represented by the equations 1 to 3, the data of only six soil samples has been used. The data of the other two samples are used for prediction. The parameters a1 and b1 are computed based on their respective initial void ratios as shown in Table 3. The predictions are shown in Figure 8 to 9. It may be of interest to note that model behaviour is agreeing very closely with experimental response.

In order to further reinforce the statements made above the data from published data of Baiji Dune soils (Abbas and Yousif, 2017) [1] has been predicted by using the model parameters proposed and these parameters as shown in Table 3. It is quite clear from the Figure 10 that the model predictions are quite satisfactory. In retrospect, the compressibility behaviour of compacted soils can be predicted by using hyperbolic approach quite satisfactory. The coefficients involved in estimating the model parameters a1 and b1 can be further refined, if more extensive data is incorporated in the development of sequence of the model proposed.

Table 3 Hyperbolic parameters

Soil sample	e_o	Model Parameters a1	Model Parameters b1
S3	0.515	16.82	4.53
S4	0.314	13.120	3.876
Baiji Dune Soils (Abbas and Yousif, 2017)*	0.641	19.149	4.953

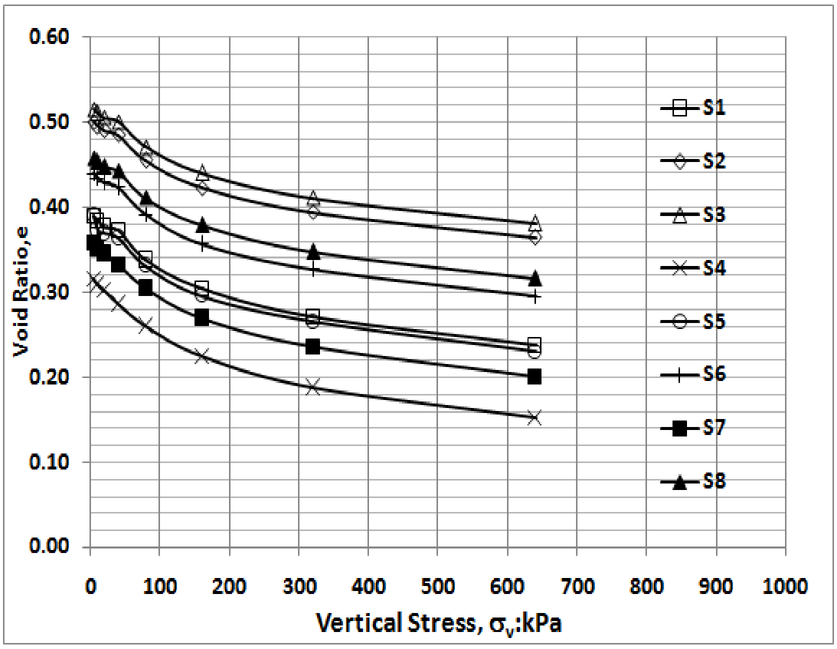

Figure 3 Compression paths of soils in 1-dimensional compression

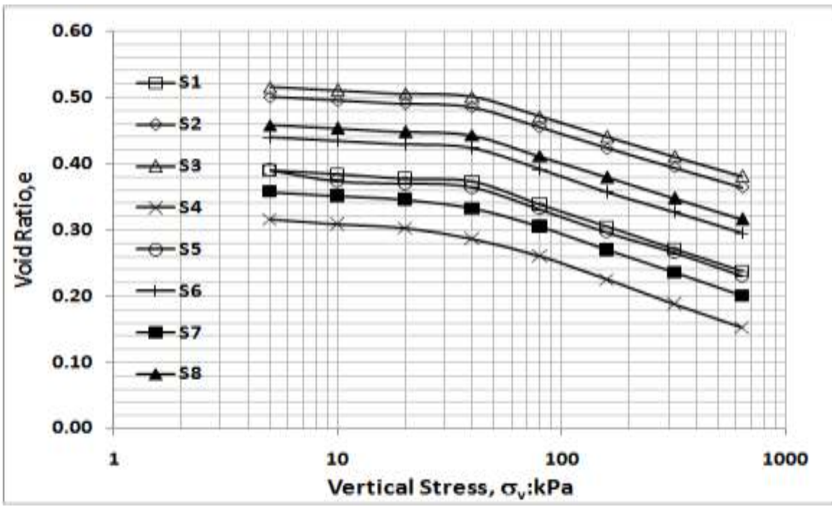

Figure 4 Compression paths of soils (log scale)

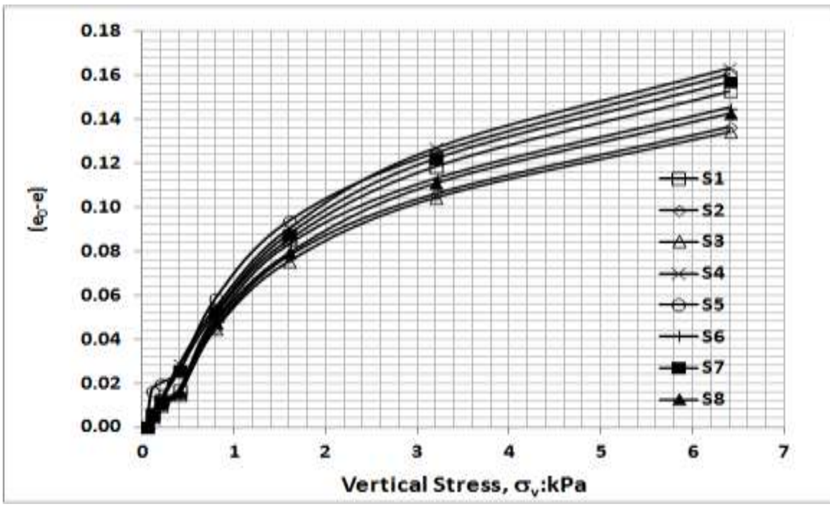

Figure 5 Compression behaviour on transformed plot

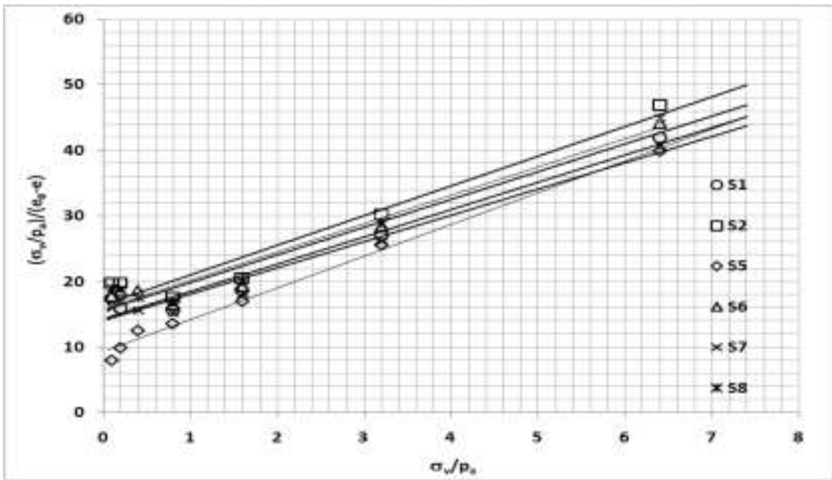

Figure 6 Linear representation of compressibility behaviour on transformed plot with data of six samples

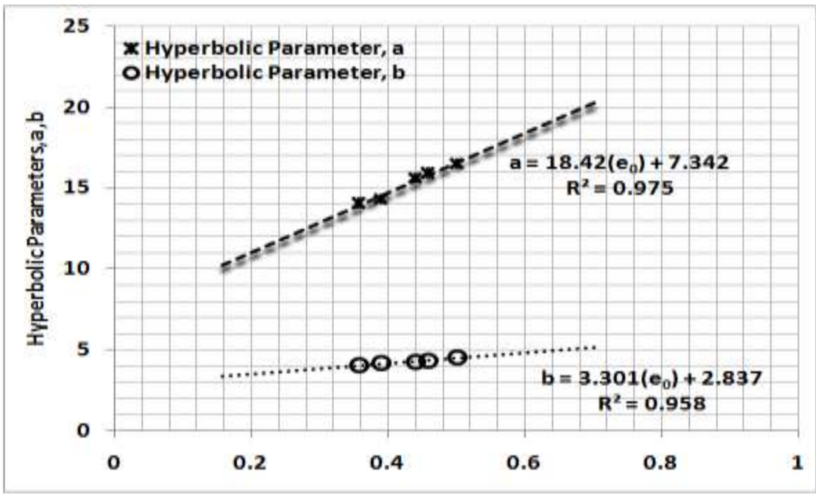

Figure 7 The relationship between hyperbolic parameters a , b with initial state represented by e_o

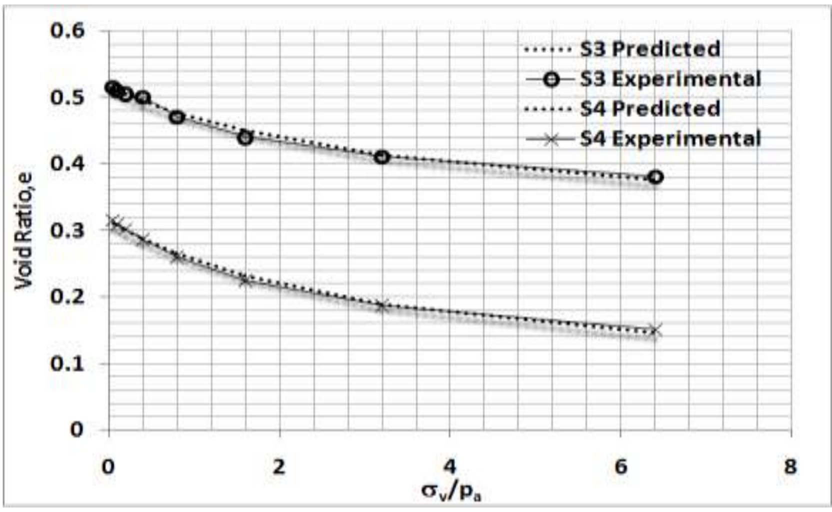

Figure 8 The relative comparison of experimental response with the model prediction

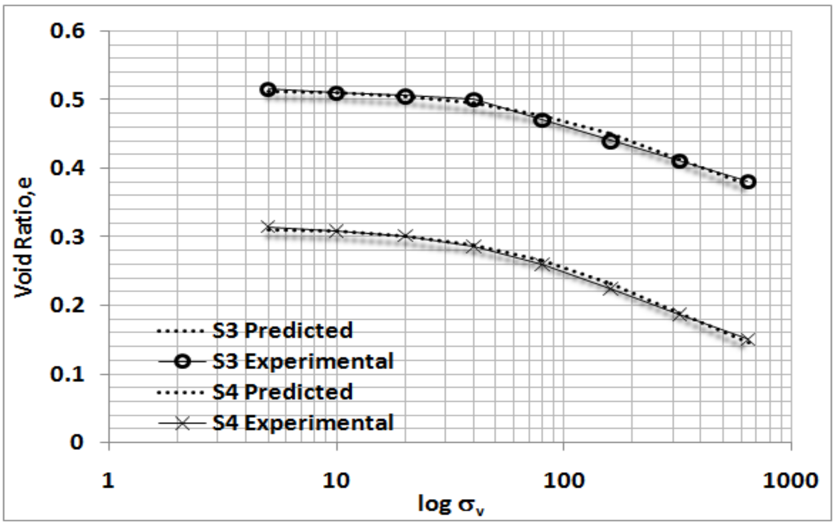

Figure 9 The relative comparison of experimental response with the model prediction

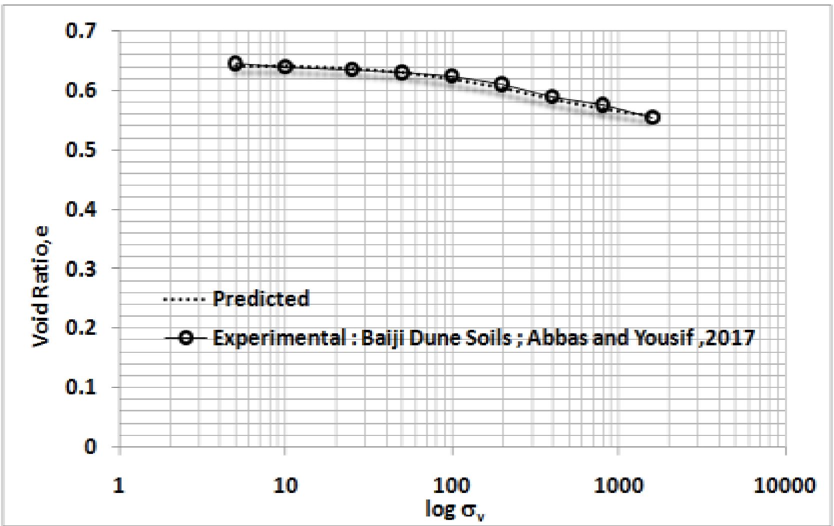

Figure 10 The relative comparison of experimental response (data from literature) with the model prediction

6. CONCLUDING REMARKS

Based on experimental investigation on eight different soils and analysis of test results, the following concluding remarks may be made.

1. The compressibility behaviour of compacted soils is observed to be non-linear.
2. The compressibility behaviour on (e_o-e) vs vertical stress is shown to exhibit hyperbolic nature.
3. The behaviour on $\frac{\sigma_v / p_a}{(e_0 - e)}$ vs σ_v / p_a is shown to be linear of the form shown $\frac{\sigma_v / p_a}{(e_0 - e)} = a1 + b1\left(\frac{\sigma_v}{p_a}\right)$.
4. The hyperbolic parameters $a1$and $b1$ are shown to be dependent on initial void ratio representing the initial state of the soil in the form shown below

   $a1 = 18.42\ (e_o) + 7.342$ with $R^2 = 0.975$

   $b1 = 3.301\ (e_o) + 2.837$ with $R^2 = 0.958$
5. The hyperbolic model proposed, predicts the compressibility behaviour quite in close agreement with the other observed response.
6. The coefficients proposed may be referred if the data of other published data is also incorporated.

ACKNOWLEDGEMENTS

The authors place on record their sincere gratitude to S.V. University, Tirupati, AP, for having provided the laboratory and computational facility while carrying out the research work cited in the present paper

REFERENCES

[1] Abbas Jawad Al-Taie and Yousif J. Al-Shakarchi. (2017) “Shear Strength, Collapsability and Compressibility Characteristics of Compacted Baiji Dune Soils”, Journal of Engineering Science and Technology, vol. 12, No. 3 (2017) 767-779.

[2] Fredlund, D. G., Morgenstern, N. R., Widger, R. A. (1978). The shear strength of unsaturated soils. Canadian Geotechnical Journal, 15:313-321, https://doi.org/10.1139/t78-029.

[3] Gens, Antonio & Sánchez, Marcelo & Sheng, Daichao. (2006). On constitutive modelling of unsaturated soils. Acta Geotechnica. 1. 137-147. 10.1007/s11440-006-0013-9.

[4] Indian Standard Classification and identification of soils for general engineering purposes. IS:1498-1970. Bureau of Indian Standard

[5] Indian Standard Method of test for soils part 1 preparation of dry soil samples for various tests. IS:2720 (part1).1983, Bureau of Indian Standard.

[6] Indian Standard Method of test for soils part 15 Determination of consolidation properties. IS:2720 (part15).1986, Bureau of Indian Standard.

[7] Indian Standard Method of test for soils part 3 determination of specific gravity Section 1 Fine Grained Soils. IS:2720 (part3).1980, Bureau of Indian Standard.

[8] Indian Standard Method of test for soils part 4 Grain size analysis. IS:2720 (part4).1985, Bureau of Indian Standard.

[9] Indian Standard Method of test for soils part 40 Determination of free swell index of soils. IS:2720 (part40).1985, Bureau of Indian Standard.

[10] Indian Standard Method of test for soils part 5 Determination of liquid limit and plastic limit. IS:2720 (part5).1985, Bureau of Indian Standard.

[11] Indian Standard Method of test for soils part 7 Determination of water content-dry density relation using light compaction. IS:2720 (part7).1980, Bureau of Indian Standard.

[12] Jennings, J. E. B., & Burland, J. B. (1962). Limitations to the Use of Effective Stresses in Partly Saturated Soils. Géotechnique, 12(2), 125–144. doi:10.1680/geot.1962.12.2.125

[13] Matsushi, Y. & Matsukura, Y. (2006). Cohesion of unsaturated residual soils as a function of volumetric water content. Bulletin of Engineering Geology and the Environment. 65. 449-455. 10.1007/s10064-005-0035-9.

[14] Sam Bulolo, Eng Choon Leong (2019). Modelling shear strength of compacted soils. E3S Web Conf. 92 15007 DOI: 10.1051/e3sconf/20199215007.

[15] Vanapalli, S.K., Sillers, W.S., and Fredlund, M.D. (1998). The meaning and relevance of residual water content to unsaturated soils. 51st Canadian Geotechnical Conference, 1998, Edmonton, pp. 101-108.

[16] Venkata Ratnam U., Nagendra Prasad K., (2019). Prediction of Compaction and Compressibility Characteristics of Compacted Soils. International Journal of Applied Engineering Research ISSN 0973-4562 volume14, Number 3, pp. 621-632.