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Numerical Modelling of Triaxial Tests for Kathmandu Soils

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Abstract
The experimental data available from triaxial tests for Kathmandu soil samples of different three places are analyzed and the characteristics are studied using three different constitutive soil models. Furthermore,the determination of stiffness and strength parameters for respective soil models are calibrated. Consolidated undrained tests for the soils of Kupondol, Jaisedewal and Gokarna at the depths of 4-6m have been modelled and the parameters are calibrated using Finite Element software. Stress paths and stress strain plots to which soil specimens were subjected in experimental triaxial tests are exercised in different soil models such that the tests are well simulated. The laboratory tests done for three different soil specimens in three different research have been used in the study. Finally, the study showed that all three constitutive models: Mohr Coulomb Model (MC), Modified Cam Clay (MCC) Model and Hardening Soil Model (HSM) were able demonstrate the soil behaviour for Jaisedewal soil. However,HSM model better illustrated the stress strain behaviour and stress paths for Kupondol soil and stress strain behaviour and pore water- axial strain behaviour for Gokarna soil.

Keywords
Soil Model, Consolidated Undrained Triaxial tests, Kathmandu soil, Stress Path, Finite Element Method

1. Introduction

Geologically, Kathmandu soils are in most part lacustrine and fluvial in origin and composed of clayey, silty, sandy and gravely sediments [1]. Central part (550 m at Bhrikutimandap) and southern part (more than 457m at Harishidhi) of the valley has the maximum thickness of the sediment [1]. The first step of the all designs in geotechnical engineering is the determination of the soil parameters. Especially, stress path exhibited by the soil is generally determined for the geotechnical problems. Other factors affecting the soil strength are such as shear strength, effective stress, plasticity, moisture content, loading rate and others. The soil strength parameters can be found using triaxial shear tests (consolidated-drained (CD), consolidated-undrained (CU), and unconsolidated undrained (UU)), direct shear test, vane shear test, unconfined compression test and others in laboratory and standard penetration test, cone penetration test, pressure meter test and others in the site. All the tests require maximum care and time because experimental errors can affect the results significantly. Also, softwares that use finite element or finite differences methods can model the soil behaviour. Thus, geotechnical problems such as bearing capacity, settlement, slope failure and many others can also be analysed using the finite element or finite differences methods. A few experimental investigations for triaxial shear tests have been found to be done in Kathmandu soils, yet very few are only collaboratively analysed and published. The consolidated undrained tests) in the Kathmandu valley, namely from the site at the left bank of Bagmati bridge in Kupondol, Lalitpur were conducted by Dhital in 2004 and the soil strength parameters were generated from the test results. Consolidated undrained test were conducted on the undisturbed sample at the depth of 4.7m from the Jaisedewal temple located south from Kathmandu's Hanuman Dhoka Durbar Square [2]. Similarly, the consolidated undrained tests were conducted on the soil sample extracted from Gokarna from a depth of 4m by Sanjiv KC , et. al. in 2016. However, use of the constitutive soil models and the parameter calibration for respective soil models for the application of FEM for further analysis and solution of geotechnical problems are found to be very limited. The study aims to use the available experimental tests results for Kathmandu soil for the best representation of the soil behavior in stress- strain and stress paths and for the parameter calibration for respective models. In the study, triaxial tests that were performed on soil samples of three different places of Kathmandu valley under different confining pressures have been modelled in FEM software and the results are compared for different soil constitutive models. The consolidated undrained tests in Kupondol soil (S1) Lalitpur [3] consolidated undrained test conducted on the undisturbed sample (S2) in Jaisedewal soil [2], 2020 and the consolidated undrained tests conducted on Gokarna soil from a depth of 4m (S3) [4] have been used for the numerical modelling. These triaxial tests were modelled in finite element software by means of axi-symmetric geometry. The Mohr Coulomb parameters and E_{50}^{ref} determined from the three triaxial test series have been used for the finite element modelling, parameter calibrations of the different soil constitutive models, determining the best suited constitutive model for the soil samples.

2. Soil models and Parameters

The finite element-based program is being extensively used for the analysis and design of geotechnical engineering projects. It can perform analysis of deformations, stability and groundwater flow in a continuum medium. It can model a broad range of soil and rock behavior because of the extensive advanced soil model's library including: linear elastic (LE), Mohr-Coulomb (MC), Hardening Soil (HS), Hardening Soil model with small-strain stiffness (HS small), Soft Soil model, Soft Soil Creep Model. It also has the possibility to incorporate user defined soil models to perform calculations. The application and appropriateness of the different soil models have been tabulated in Figure 1.

Mohr-Coulomb model is a non-linear model based on soil parameters that are simple in engineering practice. This model does not include all the non-linear features of the soil behaviour. However this model may be used to compute realistic support pressures for tunnel faces, ultimate loads for footings. Mohr-Coulomb yield condition is an extension of Coulomb's friction law to general states of stress. The Mohr-Coulomb model requires five parameters familiar to most geotechnical engineers. The parameters can be obtained from laboratory tests and tests on site in soil samples. The parameters for with their standard units are illustrated in Table 1.

The parameters of the Soft Soil Model include compression and swelling indices. The Modified Cam Clay model in the study as one of the Soft Soil models is used for the numerical modelling. Following parameters are to be determined for the Modified Cam Clay Model: Modified compression index (λ), Modified swelling index (κ), Effective cohesion(c), Friction angle, Dilatancy angle, Poisson's ratio for unloading/reloading and Coefficient of lateral stress in normal condition (K_o^{nc}).

Table 1: Parameters for Mohr-Coulomb model

SN	Parameter	Units
1	Young's modulus (E)	kN/m^2
2	Poisson's ratio (ν)	
3	Friction angle (ϕ)	$^\circ$
4	Cohesion (c)	kN/m^2
5	Dilatancy angle (ψ)	$^\circ$

The Hardening-Soil model is an advanced model for simulating the behaviour of different types of soil. The yield surface of a hardening plasticity model is not fixed in principal stress space, but plastic straining may cause its expansion [6]. Decrease in the stiffness and development of simultaneously irreversible plastic strains are seen when the model is subjected to the primary deviatoric loading. The observed relationship between the axial strain and the deviatoric stress in the exceptional situation of a drained triaxial test can be well represented by a hyperbola, [7] which is used in the well-known hyperbolic model [8]. Hardening-Soil model, however, supersedes the hyperbolic model by far using the theory of plasticity rather than the theory of elasticity , including soil dilatancy and by introducing a yield cap. The parameters used in the Hardening Soil Model are:

1. Stress dependent stiffness (m),
2. Plastic straining due to primary deviatoric loading ($E_{50}{}^{ref}$),
3. Plastic straining due to primary compression ($E_{oed}{}^{ref}$),
4. Elastic unloading / reloading ($E_{ur}{}^{ref}$) and
5. Failure according to the Mohr Coulomb model(c,ϕ, ν ,ψ)

Kupondol Clay (S1) The soil have been modelled for three confining stresses : 200 kN/m^2, 303 kN/m^2 and 415 kN/m^2 which have been identified as normally consolidated clay by Dhital, 2004. The stiffness and strength parameters as from the experimental tests are listed in Table 2.

Constitutive models	Analysis type	Soft soil			Sandy soil	Cemented clay	
		OCR > 1	OCR≈1	OCR < 1		Low compressibility	High compressibility
MC model	Serviceability limit state						
	Bearing capacity limit state	+			++	+	
DC model	Serviceability limit state	+			++	++	+
	Bearing capacity limit state	+			++	++	+
DP model	Serviceability limit state	++	+	+	++	++	++
	Bearing capacity limit state	++	+	+	++	++	++
Modified CC model	Serviceability limit state		+	+			+
	Bearing capacity limit state		++	++			++
Cap model	Serviceability limit state	+	++	++	+	+	+
	Bearing capacity limit state	++	++	++	++	++	++
HS model	Serviceability limit state	+++	++	++	+++	+++	+++
	Bearing capacity limit state	+++	++	++	+++	+++	+++

OCR: over consolidation ratio; +: generally applicable, the effect is not ideal; ++: applicable, good effect; +++: applicable, very good effect.

Figure 1: Appropriateness of different constitutive soil models [5]

Table 2: Parameters from Consolidated Undrained triaxial tests for Kupondol Soil [3]

SN	Parameter	Values
1	Depth (m)	4.5-6
2	Plasticity Index (%)	14-22.44
3	Wet Density (gm/cm^3)	1.28-1.55
4	Organic Matter (%)	8.31-13.07
5	c (kN/m^2)	40.9
6	Friction angle (ϕ)(°)	17
7	c' (kN/m^2)	53.8
8	Effective Friction angle (ϕ')(°)	17
9	M	1.2
10	$E50^{ref}$ (kN/m^2)	6000
11	λ	0.302
12	κ	0.019

Jaisedewal soil (S2): The monotonic consolidated undrained tests were conducted on the Jaisedewal soil at the confining pressures of 100 kPa, 200 kPa and 300 kPa by Kumar, 2020 [2]. It was observed that the peak deviator stress-strain response attained peak stress at the axial strain of 5 percentage [2]. Table 4 illustrates the parameters obtained from study and the results of the tests are listed in Table 3.

Gokarna soil (S3): Fundamental properties of the soil samples, uniaxial compressive strength tests and consolidated undrained triaxial tests of Gokarna formation samples were conducted by Sanjiv KC et.al., in 2016 [4]. The tests results shown in Table 4 from the consolidated undrained triaxial tests for the soil samples at the depth of 4m have been used in this study.

Table 3: Parameters from Consolidated Undrained triaxial tests for Jaisedewal Soil [2]

SN	Parameter	Values
1	Depth (m)	4.7
2	Plasticity Index (%)	22
3	Wet Density (gm/cm^3)	1.86
4	c (kN/m^2)	0
5	Friction angle (ϕ)(°)	33
6	M	1.36
7	E_{50}^{ref} (kN/m^2)	9000

Table 4: Parameters from Consolidated Undrained triaxial tests for Gokarna Soil [4]

SN	Parameter	Values
1	Depth (m)	4
2	Plasticity Index (%)	30.3
3	Wet Density (gm/cm^3)	1.076
4	c (kN/m^2)	14.63
5	Friction angle (ϕ)(°)	30.67

3. Modelling

The triaxial tests were modelled in finite element software by the use of axi-symmetry geometry of 1m $\times$ 1m unit dimension which represented the one quarter of the soil sample since unrealistically large dimension of the model did not influence the results as the soil sample was set as a weightless material [9]. A quadrant of the soil sample was represented by the triaxial model's simplified geometry. The upper and left bounds were left open to allow for smooth movement along the axes of symmetry, whereas the deformations perpendicular to the boundaries were fixed. Lower and right boundaries were permitted to shift, similar to the triaxial test's boundary condition. The applied deviator stress and confining pressure were simulated as a distributed load system.

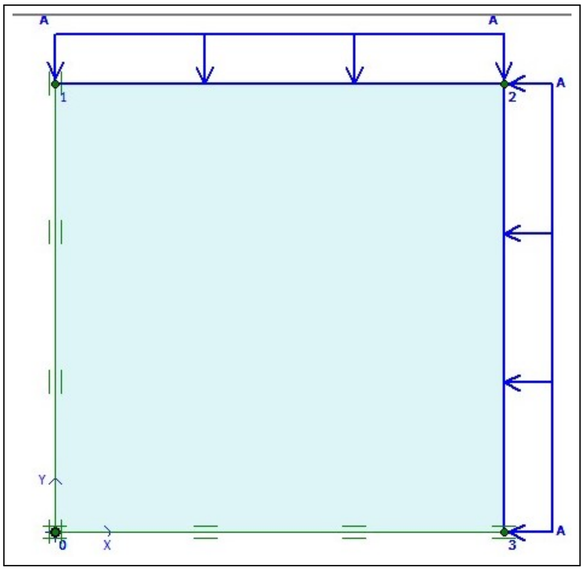

Figure 2: Model Screen for Triaxial Test

Mohr columb model (MC) model, Modified Cam Clay (MCC) model and Hardening Soil Model (HSM) have been used for the simulation of both the Kupondol soil, Jaisedewal soil while Hardening Soil Model (HSM) has been used for Gokarna soil. The soil has been modelled in the 15-node element type with the medium mesh coarseness for the element distribution. Two phases Consolidation phase and shearing phase have been calculated as the plastic analysis where undrained material type conditions was ignored by selecting the ignore undrained behaviour in the consolidation phase of the calculation. The soil model was analysed under different confining pressures . The consolidation phase was followed by the shearing phase where the deviotoric stress was added to the vertical stress and the soil collapsed before reaching the ultimate state.

4. Results and Discussion

The Kupondol Soil (S1) was simulated for the stress-strain plot and stress paths to best demonstrate the soil behaviour using Mohr Coulomb Model (MC), Modified Cam Clay Model (MCC) and Hardening soil model (HSM) and the comparison was made for the determination of appropriate soil model for further study. The soil parameters have also been calibrated for the respective soil models. The confining pressures used were $200kN/m^2$, $303kN/m^2$ and $415kN/m^2$.

Figure 3 shows the plot for the stress strain and and figure 4 shows the stress paths for different soil models for the soil. The Hardening Soil Model best demonstrated the soil behaviour for the Kupondol soil. Also the soil parameter calibrated for all three constitutive models are illustrated in Table 5.

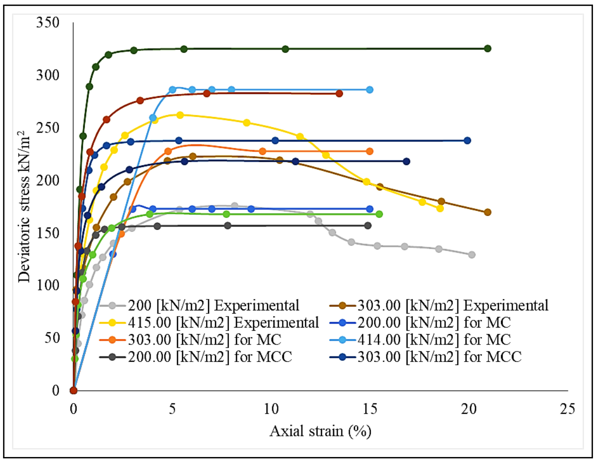

Figure 3: Stress strain plots for S1

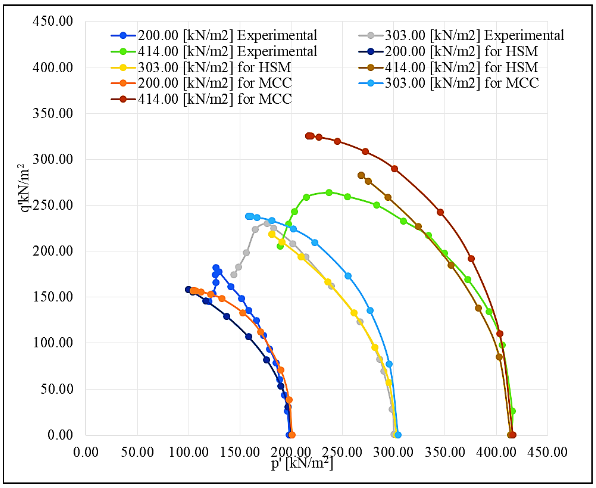

Figure 4: Stress paths for S1

Table 5: Parameters calibrated for S1

MC	MCC	HSM
E- 6000kN/m^2 ν-0.2 ϕ - 14° c-38kN/m^2 ψ-0°	λ-0.302 ν-0.2 ϕ - 17° c-40 kN/m^2 ψ-0° κ - 0.019 M-1.32	E_{50}^{reF} $-8000kN/m^2$ ν-0.2 ϕ - 19.2° c-40.9 kN/m^2 ψ-0° $E_{oed}{}^{ref}$-4000 kN/m^2 $E_{ur}{}^{ref}$-30000 kN/m^2

The Jaisedewal Soil (S2) was simulated for the stress-strain plot and stress paths to best demonstrate the soil behaviour using Mohr Coulomb Model(MC), Modified Cam Clay Model(MCC) and Hardening soil model and the comparison was made for the determination of appropriate soil model for further study. The soil parameters have also been calibrated for the respective soil models. The confining pressures used were $100kN/m^2$, $200kN/m^2$ and $300kN/m^2$ in the experimental tests while they have been adjusted to $100kN/m^2$, $175kN/m^2$ and $290kN/m^2$ for Modified Cam Clay model(MCC) and Hardening Soil Model (HSM) to simulate the soil behaviour due to the unusual nature of the stress path in the initial loading condition in the Figure 6. This portion of the plot might be due to the presence of organic matter, highly compressible material, impurities or larger void ratio in the soil sample. Figure 5 and Figure 6 are the plots for stress-strain and stress paths for the soil respectively obtained from the analysis.

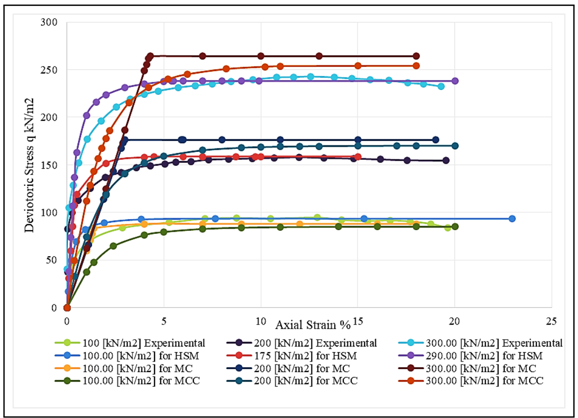

Figure 5: Stress strain plots for S2

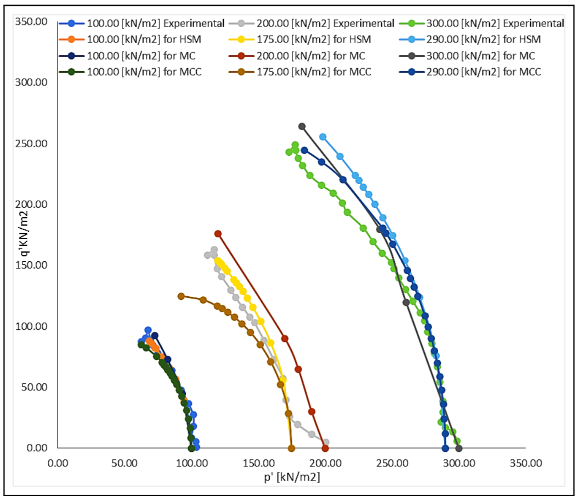

Figure 6: Stress paths for S2

From the plots we can derive that all three models are quite relevant to well demonstrate the soil behaviour while the plots from MCC and HSM are more closer than that of MC model. The parameters calibrated for all three constitutive models for Jaisedewal soil are illustrated in Table 6.

Table 6: Parameters calibrated for S2

MC	MCC	HSM
E- 3000kN/m^2	λ-0.25	E_{50}^{ref}-8000kN/m^2
ν-0.2	ν-0.2	ν-0.2
ϕ - 22.5°	ϕ - 32°	ϕ - 32°
c-0 kN/m^2	c-0 kN/m^2	c-0 kN/m^2
ψ-0°	ψ-0°	ψ-0°
	κ-0.08	$E_{oed}{}^{ref}$-3500 kN/m^2
	M-1.36	$E_{ur}{}^{ref}$-60000 kN/m^2

The Gokarna Soil (S3) was simulated for the stress-strain plot and the pore pressure against deviatoric plot study since the stress paths of the respective soil was not available for the study. The stress strain behaviour and pore water pressures was modelled using Hardening soil model and the soil parameters have also been calibrated for the soil model. The confining pressures used were 98.1 kN/m^2, 196.2 kN/m^2 and $294.4kN/m^2$ Hardening Soil Model (HSM) in the study to best represent the stress strain Behavior as in Figure 7 and pore water-axial strain behaviour as in Figure 8.

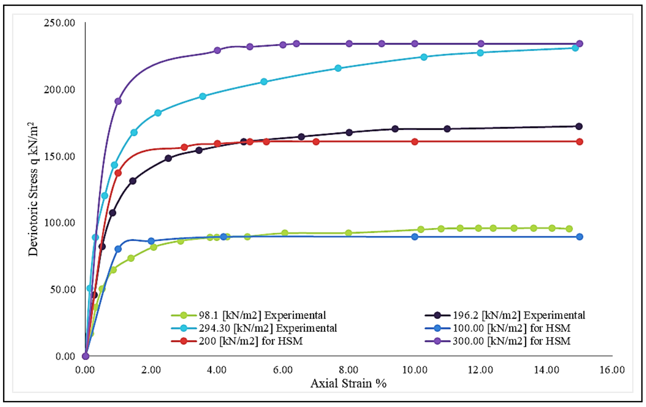

Figure 7: Stress strain plots for S3 for HSM

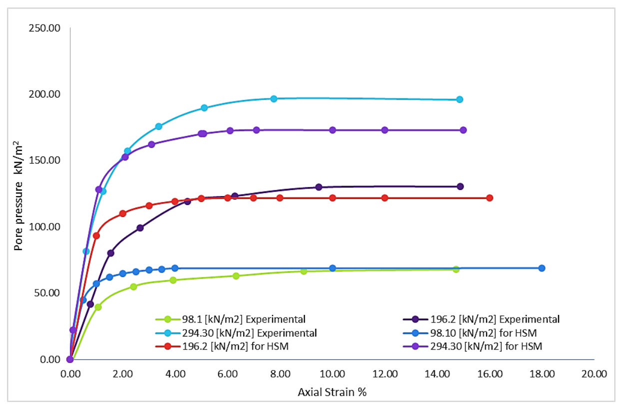

Figure 8: Pore Pressure Strain Plots for S3 for HSM

Table 7: Parameters calibrated for S3

Parameters calibrated for HSM	values
E	8000 kN/m^2
ν	0.2
ϕ	27.5°
c	12 kN$/m^2$
ψ	0°
Eoed^{ref}	5000 kN$/m^2$
Eur^{ref}	53333 kN$/m^2$

Conclusion

The study was focused on the simulation of triaxial tests on the Kathmandu soil of three different places with different soil properties as available in the literature and analysed using the Finite Element Software for three different constitutive models. The soil parameters for all three models for Kupondol and Jaisedewa soils have been calibrated and the soil parameters for HSM have been calibrated for Gokarna Soil.

1. HSM model better illustrated the stress strain behaviour and stress paths for Kupondol soil and stress strain behaviour and pore water-axial strain behaviour for Gokarna soil while all three constitutive models i.e. HSM, MCC model and MC model were found good for representing the soil in stress strain behaviour and stress paths for Jaisedewal soil. However, the HSM and MCC model were more closer for higher confining stresses for Jaisedewal soil.
2. The calibrated parameters for Mohr Coulomb model were found to be more on the lower side than that from MCC and HSM for all three soils.
3. As the confining pressures increase the undrained strength for all the soil models were increased in the analysis compared to the test results.
4. None of the soil models were able to model the soil softening behaviour in the soils in the used commercially available FEM software. Hence, it is recommended for the further study to simulate the softening behaviour of the soil as well.

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