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Prediction of Cyclic Behaviour of Quaternary Alluvial Soil using Finite Element Approach

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Abstract – This paper presents a numerical simulation to describe the stress-strain responses of sands under large strain cyclic loading using the finite element method. Initially a class C1 Prediction has been performed using two different fully-coupled effective stress constitutive modelling. The calibrated model has been validated further against the experimental data from displacement controlled cyclic triaxial tests for different alluvial soils. In the last part, a parametric study has been conducted to predict the cyclic behaviour and dynamic properties of sands available in the alluvial deposits for variation in site and motion characteristics. The study demonstrates that the proposed model can be used with caution by geotechnical engineer to predict the large strain cyclic behaviour of similar types of sand available worldwide in the alluvial deposits.

Keywords**:** Finite Element Method, Class C1 Prediction, Alluvial Soil, Large Strain Cyclic Behaviour

1. Introduction

Soil-liquefaction related hazards can severely damage structures and also can result in considerable loss of life and property. Therefore, it is important to evaluate the stability of site against soil liquefaction. However, the level of shaking can vary depending on loading type such as traffic loading, blasting, seismic activity etc. Therefore, it is necessary to obtain the dynamic properties over a range of confining pressure considering different site conditions. As mentioned in the literature, this can be accomplished at the laboratory either (a) by using a multistage test, where a specimen is tested at any particular confining pressure and subsequently tested at other confining pressure values or (b) by performing several single stage tests where the specimen is subjected to a confining pressure and then tested at a range of shear strain [1]. However, both methods involve sophisticated costly apparatus to conduct the experimental investigation and also highly time consuming. Therefore, for several decades the scientist have tried to discover different alternative approaches to overcome such problems. One such method is constitutive modelling of the soil behaviour. Those constitutive relationship depends on pressure and void ratio as well as the nonlinear behaviour of the sand matrix [2]. Therefore, sometime the most sophisticated models cannot provide accurate predictions under general cyclic loading [3]. Thus development of a reliable model to capture the cyclic behaviour is one of the major challenging issues in constitutive modelling [4].

As evidenced from the earthquake data, an alluvial plain is most prone to liquefaction as they have thick deposits of fine sand layer at the shallow depth. One of such alluvial deposits is the Indo-Gangetic Plain which lies on the earthquake prone Himalayan region. For decades a number of researches have been carried out to determine the dynamic properties and cyclic behaviour of soil using experimental and numerical investigation [5]–[7]. However, only a few studies used FE approach to simulate the cyclic behaviour of soil in cyclic triaxial test [8]. Therefore, in this study, an axisymmetric model has been built up in the commercial software PLAXIS 3D. The effect of effective confining stress, motion amplitude and motion frequency on the cyclic behaviour of soil has been studied here in this study. In addition, a MATLAB code (shown in APPENDIX) has been developed to process the results obtained from PLAXIS 3D and to determine the dynamic properties from the hysteresis loop obtained from numerical simulation.

The methodology of this present study (shown in Fig. 1) includes the validation of model parameters by doing Class C1 prediction, which was performed to increase the reliability of the selected constitutive model as well as the parameters used in the constitutive model. A Class C1 prediction can be made after the event and the results are known at the time of prediction [9]. The constitutive model and modelling parameters are calibrated herein based on the cyclic triaxial test on the Solani Sand from Upper Ganga Plain (UGP). The calibrated model further verified by comparing the cyclic behaviour of soil obtained from displacement controlled cyclic triaxial test executed on sand from Middle Ganga Plain (MGP), Lower Ganga Plain (LGP) and Brahmaputra Plain. From the results and revisiting the cyclic behaviour of the sand from the alluvial deposits available in the literature it can be concluded that the cyclic behaviour of the alluvial soil can be predicted using this proposed constitutive model if they have similar grain size distribution curves.

2. Numerical Simulation

The dynamic finite element analysis of the displacement controlled cyclic triaxial test has been simulated using two different finite element based numerical scheme. Both scheme used effective stress based fully-coupled approach to model the undrained shear behaviour of alluvial soil under cyclic loading. In this study, axisymmetric condition of a triaxial sample has been modelled. Boundary conditions are crucial for this axisymmetric triaxial test. The dynamic boundary has been considered as viscous boundary where the surfaces are free. 16 Nodded 12106 number elements have been used in this model.

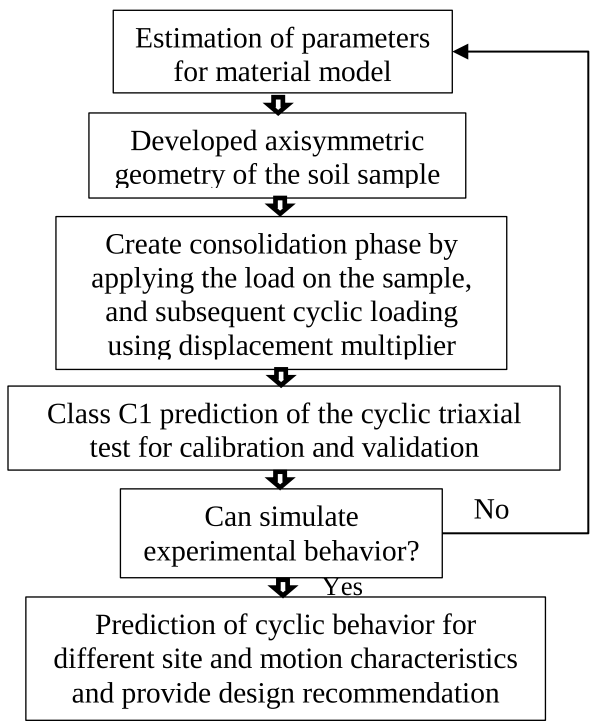

Fig. 1: Methodology of the present study

2.1. UBC-3D PLM Model

The UBC-3D PLM model is an advanced model that can simulate the liquefaction behaviour of soil under cyclic loading. This model uses the well-known Mohr- Coulomb yield function generalized in 3-D principal stress space. The elastic response of this model is assumed to be isotropic. The plastic response or the plastic strain rates are controlled by the yield loci that are assumed to be radial lines with their origin in stress space. Different fitting parameters such as f_{dens}, f_{Epost} also introduced in this model to control the plasticity hardening and hysteresis loop details [10]. The detailed input parameters used in this model are briefed in Table 1.

2.2. HSsmall Model

This is an elastoplastic type of hyperbolic model, similar to the Hardening Soil model. Moreover, this model incorporates strain dependent stiffness moduli, simulating the different reactions of soils from small strains (for example vibrations with strain levels below 10^{-5}) to large strains (engineering strain levels above 10^{-3})[11]. The major drawbacks in the initial HS model formulation was the lack of proper modelling of the small strain behvaiour and therefore Benz and co-workers [12], [13] proposed this present HSsmall model used in this study. This model is entirely isotropic in both elastic and elasto-plastic ranges. The detailed in put parameter of this model are also given in Table 1.

Table 1: Input parameters for cyclic test verification for Solani sand (Modified after Kanth and Maheswari 2021[8])

UBC-3D PLM Model		**HS Small Model**	
Parameters	**Value**	**Parameters**	**Value**
Peak friction angle φ_p (Deg)	31.3	Saturated weight density, γ_{sat} (kN/m^3)	19.5
Phase transformation friction angle φ_{cv} (Deg)	30.2	Unsaturated weight density, γ_{unsat} (kN/m^3)	15.46
Elastic bulk modulus number $k^e{}_B$	702	Friction angle φ (Deg)	35
Elastic shear modulus number $K^e{}_G$	1003	Dilatancy angle φ (Deg)	5
Plastic shear modulus number $k^e{}_p$	1364	Cohesion, c' (kPa)	5
Exponent for stress dependency of elastic bulk modulus me	0.5	Coefficient of lateral earth pressure, K_0^{nc}	0.391
Exponent for stress dependency of elastic shear modulus ne	0.5	Initial (small-strain) shear modulus G_0 (MPa)	100
Power for stress dependency of plastic shear modulus np	0.4	Shear strain corresponding to $0.7G_0, \gamma_{0.7}$	0.00015
Failure ratio R_f	0.77	Tangent oedometric stiffness, $E_{oed}{}^{ref}$ (MPa)	30
Reference stress p_{ref} (kPa)	100	Secant stiffness in drained triaxial test, $E_{50}{}^{ref}$ (MPa)	30
Fitting parameter to adjust number of cycles to liquefaction f_{dens}	1	Unloading/reloading stiffness, $E_{ur}{}^{ref}$ (MPa)	60
Fitting parameter to adjust post-dilation behaviour f_{Epost}	0.25	Unloading/reloading Poisson's ratio	0.2
Corrected SPT blow counts $(N_1)_{60}$	11.11	Failure ratio R_f	0.81

3. Calibration and/or Verification of Material Model

The compression has been considered as negative and tension as positive in PLAXIS. Therefore, after simulating the model the results have been processed to compare with the experimental results and further MATLAB code (as shown in APPENDIX) has been used to determine the dynamic properties for the parametric study. The simulated results have been compared with the experimental results. For comparison, average deviatoric stress has been considered in the present study. The average deviatoric stress is considered the deviatoric stress developed under compression as well as tension and can be calculated as

$$average\ deviatoric\ stress = \left(\frac{\left|\sigma_{\mathrm{d}\ max_{Comp}}\right| + \left|\sigma_{\mathrm{d}\ max_{ext}}\right|}{2}\right)$$

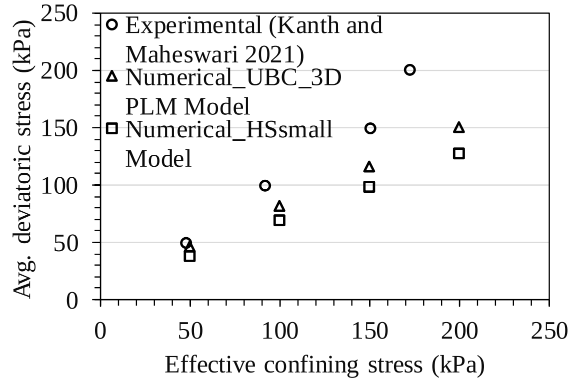

Fig. 2: Comparison between experimental and computed numerical results using UBC and HSsmall model

It can be observed from the Fig. 2 that UBC-sand model can simulate the large strain cyclic behaviour of Solani sand better than HSsmall soil model. The reason behind it could be during small strain due to the uncontrolled reset of the loading memory and regain of high initial stiffness after tiny unloading-reloading cycle. This problem is also known as overshooting as mentioned in the literature.

Further, for the verification of the soil model the peak average stress ratio (i.e., $ASR_{peak} = \frac{\left|\frac{\sigma_{d\,max_{Comp}}}{2\sigma_3'}\right| + \left|\frac{\sigma_{d\,max_{ext}}}{2\sigma_3'}\right|}{2}$) obtained from the numerical simulation has been compared with the results available for Middle Ganga Plain (MGP) sand [7] from the Indo-Gangetic Plain. A good match has been obtained between experimental and simulated results in terms of average peak stress ratio. One major reason behind the similarity could be the grain size distribution of both sands. Basically, the range of particle size indicates that fine sand particles dominates the both sand matrix. Therefore, it can be concluded that the alluvial sands having a similar GSD curve can show similar behaviour under cyclic loading and thus this model can be used to simulate the behaviour of a similar type of alluvial soils with caution.

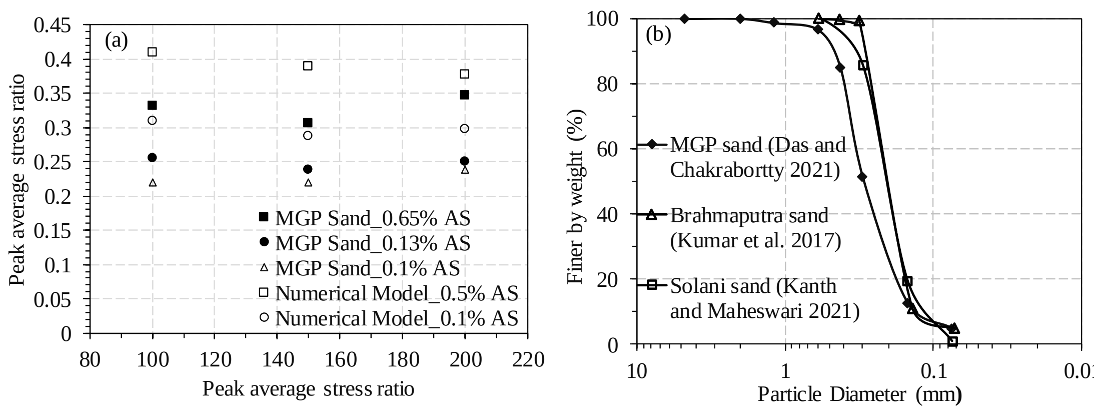

Fig. 3: (a) Comparison between experimental and computed numerical results in terms of peak average stress ratio (AS denotes axial strain), (b) Grain size distribution of different alluvial sands used in this study

4. Parametric Study

4.1. Effect of motion parameters and site characteristics on stress-strain behaviour

The effect of motion amplitude on the cyclic behaviour of soil for different effective confining stress has been shown here in Fig. 4a. It can be observed from the figure that with the increase in the motion amplitude, more stress is induced on the soil grain in the initial cycle. It can also be inferred from the figure that the resistance of soil against the deformation increases with the increase of the overburden pressure or effective confining stress. Basically, with the increase in the confinement, the soil grains are in more compacted condition and thus, the resistance towards the cyclic load increased. The other studied parameter motion frequency doesn't show much impact on the stress-strain behaviour under intermediate or large strain range as shown in Fig. 4b. A similar observation can be found in the literature for large large strain cyclic behaviour of different alluvial soils [5], [7].

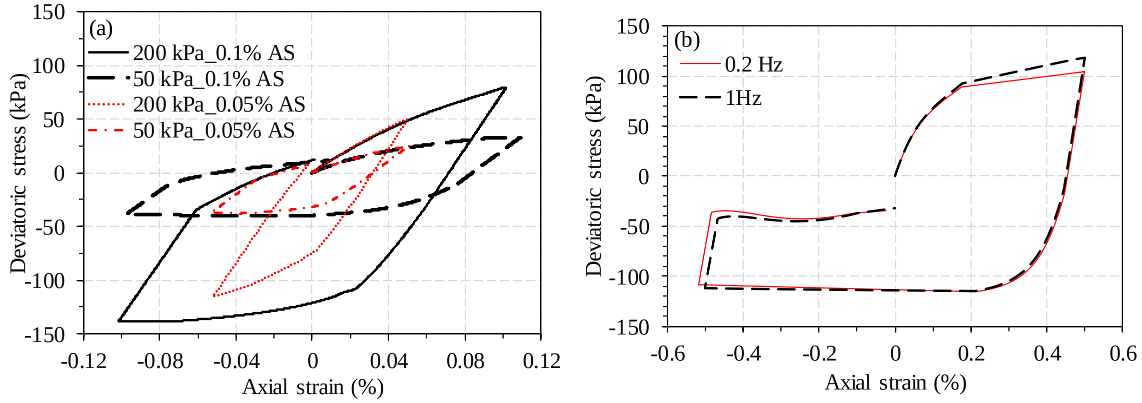

Fig. 4: (a) Computed stress strain history of initial cycles for different strain amplitude and effective confining stress; (b) impact of motion frequency on large strain cyclic behaviour of soil

4.2. Effect of motion parameters and site characteristics on EPWP ratio

The effect of motion and site characteristics on the developed EPWP ratio is shown here in the Fig. 5. It can be observed from the figure that the EPWP ratio developed in the soil increases with the increase in the displacement amplitude of the motion. This indicates that as the motion amplitude increases the soil liquefies more quickly. However, with the increase in the effective confining stress or overburden pressure the developed EPWP ratio in the soil decreases. It can also be inferred from the Fig. 5 is that at large strain the difference in the EPWP development due to different in confining pressure is less compare to that at lower strain. It indicates that at large strain the overburden pressure have less impact on soil liquefaction.

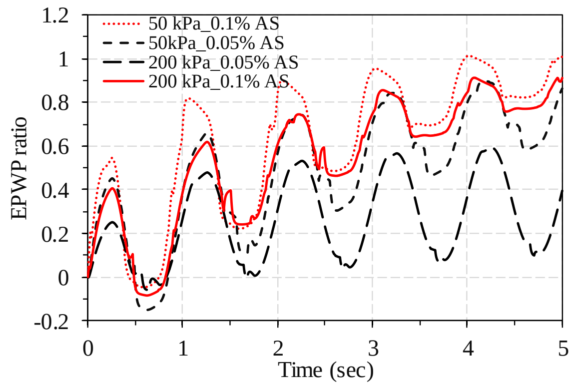

Fig. 5: Computed EPWP ratio and time history for different strain amplitude and effective confining stress

4.3. Effect of motion parameters and site characteristics on Dynamic properties

The effect of motion and site characteristics on the dynamic properties of soil has been computed further using the calibrated UBC-3D-PLM model and additional MATLAB code (detailed in APPENDIX). It can be observed from the Fig. 6 is that the variation in the dynamic properties for variation in the motion amplitude and effective confining pressure is similar to the experimental observation on other alluvial sands [5], [7], [14], [15]. It can be observed that the shear modulus of soil increases with the increase in the effective confining stress and decreases with the increases in the motion amplitude. However, damping ratio of soil increases with the increase in the strain amplitude.

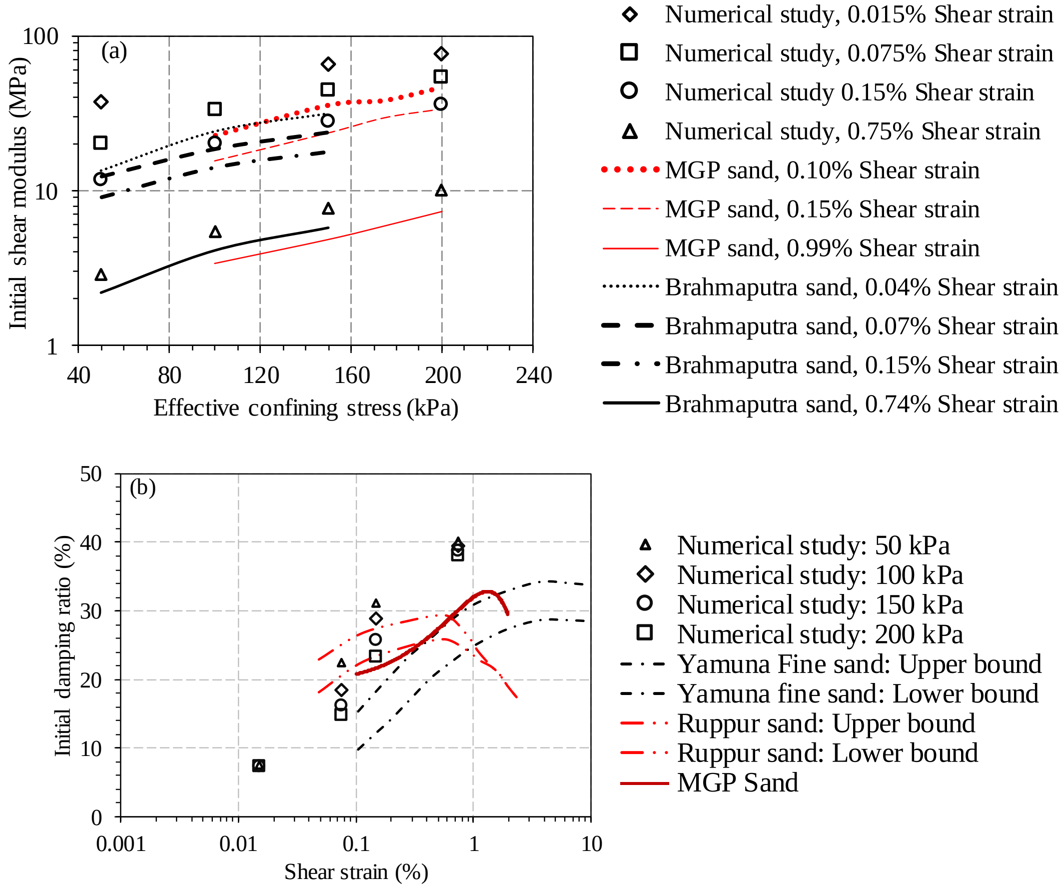

Fig. 6: Variation in computed (a) initial shear modulus and (b) damping ratio with effective confining stress for different strain amplitude along with the experimental results on different alluvial sands available worldwide

5. Conclusions

This paper presents a prediction of the cyclic behaviour and shear modulus using effective stress based coupled three dimensional finite element approach. Initially the soil model has been calibrated by comparing it with experimental results on Solani sand. In addition, the calibrated model has been verified using the experimental observation on some other alluvial soils such as MGP sand and Brahmaputra sand. Finally, a parametric study has been conducted using the calibrated numerical model to determine the effect of site and motion characteristics on the large strain cyclic behaviour of soil. The overall study can be concluded as follows-

The UBC sand model is found to be more effective compared to the HSsmall model in modelling the large strain cyclic behaviour of soil.

For the studied range of site and motion characteristics the effective confining stress or overburden pressure and motion amplitude have more impact on the large strain cyclic behaviour of soil compared to the motion frequency.

The study shows that the sand available in different alluvial deposits shows similar cyclic behaviour. The reason behind it could be the similarity in their grain size distribution curves. Therefore, geotechnical engineer can use this model with caution to estimate the large strain cyclic behaviour of similar type of alluvial sands.

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References

[1] H. B. Seed, K. Tokimatsu, L. F. Harder, and R. Chung, "The influence of SPT procedures on soil liquefaction resistance evaluations.," Report No. UCB\EERC-84/15, Earthquake Engineering Research Center, University of California, Berkeley, CA, 1984.

[2] N. Khalili, M. A. Habte, and S. Valliappan, "A bounding surface plasticity model for cyclic loading of granular soils," *Int. J. Numer. Methods Eng.*, vol. 63, no. 14, pp. 1939–1960, 2005.

[3] M. P. O'Reilly and S. F. Brown, *Cyclic loading of soils: from theory to design*. Blackie Glasgow, UK, 1991.

[4] P. A. Vermeer and R. De Borst, "Non-associated plasticity for soils, concrete and rock," *HERON, 29 (3), 1984*, 1984.

[5] S. S. Kumar, A. M. Krishna, and A. Dey, "Evaluation of dynamic properties of sandy soil at high cyclic strains," *Soil Dyn. Earthq. Eng.*, vol. 99, no. April, pp. 157–167, 2017, doi: 10.1016/j.soildyn.2017.05.016.

[6] R. Varghese, M. S. Amuthan, A. Boominathan, and S. Banerjee, "Cyclic and postcyclic behaviour of silts and silty sands from the Indo Gangetic Plain," *Soil Dyn. Earthq. Eng.*, vol. 125, p. 105750, 2019.

[7] A. Das and P. Chakrabortty, "Large strain dynamic characteristics of quaternary alluvium sand with emphasis on empirical pore water pressure generation model," *Eur. J. Environ. Civ. Eng.*, pp. 1–24, 2021.

[8] A. Kanth and B. K. Maheshwari, "Behaviour of Solani sand under monotonic and cyclic loading: experiments and finite element simulations," *Int. J. Geotech. Eng.*, pp. 1–14, 2021.

[9] T. W. Lambe, "Predictions in soil engineering," *Géotechnique*, vol. 23, no. 2, pp. 151–202, 1973.

[10] S. Giridharan, S. Gowda, D. F. E. Stolle, and C. Moormann, "Comparison of ubcsand and hypoplastic soil model predictions using the material point method," *Soils Found.*, vol. 60, no. 4, pp. 989–1000, 2020.

[11] R. Luna and H. Jadi, "Determination of dynamic soil properties using geophysical methods," in *In 1st International Conference on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure, St. Louis, MO*, 2000, pp. 1–15.

[12] T. Benz, *Small-strain stiffness of soils and its numerical consequences*, vol. 5. Univ. Stuttgart, Inst. f. Geotechnik Stuttgart, 2007.

[13] T. Benz, P. A. Vermeer, and R. Schwab, "A small-strain overlay model," *Int. J. Numer. Anal. methods Geomech.*, vol. 33, no. 1, pp. 25–44, 2009.

[14] N. Puri, A. Jain, G. Nikitas, P. K. Dammala, and S. Bhattacharya, "Dynamic soil properties and seismic ground response analysis for North Indian seismic belt subjected to the great Himalayan earthquakes," *Nat. Hazards*, vol. 103, pp. 447–478, 2020.

[15] M. Mominul Hoque, "Evaluation of dynamic properties of a sandy soil using cyclic triaxial test," Department of Civil Engineering, Bangladesh University of Engineering and Technology, 2016.

APPENDIX: MATLAB Code for Determination Dynamic Properties from Hysteresis Loop

```
clear all;
close all;
clc;
format compact;
miu = 0.5; %miu
path_to_file = "C:\Users\Rohan Deb\Desktop\From Lab to Smail\Dynamics lab\Angsuman da\Rohan_calculation shear
        modulus damping ratio.xlsx";
taable = xlsread(path_to_file);
zz = 3
time_log = taable(1:end,1+4*zz);
ht_of_sample = taable(1:end,2+4*zz);
load_input = taable(1:end,3+4*zz);
k(1)=1;
for i = 1: max (time_log)
     k(i+1) = max(find (time_log== i));
     min_smpl_ht(i) = min(ht_of_sample( k(i): k(i+1)) );   % no of element = total Sec
     max_smpl_ht(i) = max(ht_of_sample( k(i): k(i+1)) );   % no of element = total Sec
     min_load(i) = min(load_input( k(i): k(i+1)) )        % no of element = total Sec
     max_load(i) = max(load_input( k(i): k(i+1)) )        % no of element = total Sec
end
for j= 1:(length (ht_of_sample)-1)
    Work(j) = 0.5*(load_input(j)+load_input(j+1))* (ht_of_sample(j+1)- ht_of_sample(j));
end
%No of Elements in this matrix = ht_of_sample - 1;
for n=1:i
    AL(n)= sum(Work(k(n):k(n+1)-1));
end
% no of element = total Sec
A_Delta=(0.5* abs(max_load.* max_smpl_ht+ min_load.* min_smpl_ht)+ abs(max_smpl_ht.*min_load));
A_Delta_Mod= (0.5* abs(max_load.* max_smpl_ht+ min_load.* min_smpl_ht))/2;
Damping_ASHL =     AL*100./(pi*A_Delta);
Damping_ASHL_Mod =     AL*100./(4*pi*A_Delta_Mod);
Total_Load = max_load + abs(min_load)
Total_Strain =  max_smpl_ht + abs(min_smpl_ht)
% E =  (Total_Load*hac)./(Total_Strain*a0);
E =  (Total_Load)./(Total_Strain)
G =  (E)/(2*(1+miu))
```