

## 2D Numerical Modeling of the Cyclic Simple Shear Test Using Opensees

Saeedullah Jan Mandokhail<sup>1</sup>, Nawaz Ali<sup>1</sup>, Mohammad Siddique<sup>2</sup>, Ehsanullah Kakar<sup>1</sup>, Ali Nawaz Mengal<sup>3</sup>, Ghulamullah Kakar<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, <sup>2</sup>Department of Chemical Engineering, <sup>3</sup>Department of Mechanical Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan.

### Abstract

*Simple Shear (SS) test is considered to simulate the in-situ stress conditions more accurately than any other testing system. Undrained Cyclic Simple Shear test is extensively performed to evaluate the cyclic shear strength and liquefaction potential of soil. In this study, the numerical modeling of the SS testing was undertaken using a finite element method (FEM) in the Opensees (Open System for Earthquake Engineering Simulation). The study showed that FEM simulation can efficiently capture the cyclic shear behavior and the excess pore water pressure development. The analysis results were also compared with the laboratory measurements and shown to satisfactorily match the measurements.*

**Keywords:** Cyclic shear strength; Liquefaction resistance; Simple shear test; Opensees

**Corresponding Author's email:** saeed.ullah@buitms.edu.pk

## INTRODUCTION

The simple shear (SS) test has been extensively used to determine the soil behavior particularly under cyclic loading condition (Bjerrum and Landva 1966; Finn et al., 1982; Ishihara and Yamazaki, 1980). The main advantage of the SS test is that it provides more realistic simulations of in-situ stress conditions including  $k_0$  condition (at rest condition), rotation of principal plane and vertically propagating shear waves induced by earthquake loading. Figure 1 schematically illustrates the applied loading conditions during consolidation and shearing phase of SS test. The lateral confinement of the specimen is provided by a reinforced wire membrane or stack of rings.

Although the SS test is simple to perform, the availability of the equipment and quality sample is always a challenge. In this paper, the SS test is modeled using OpenSees coding system. OpenSees (Open System for Earthquake Engineering Simulation) is an open-source finite element software which utilizes a wide range of elements, material models, and solution algorithms, providing a platform for simulating the seismic response of structural geotechnical systems (Mazzoni et al., 2010). OpenSees is able to analyze linear and non-linear soil, structures, and soil-structure systems subjected to static and cyclic loading. It uses Tcl, a fully programmable scripting language, for input files, which provides a great deal of power and flexibility. Most of the geotechnical capabilities including elements and constitutive models, were developed by researchers at the University of California at San Diego (UCSD) (Yang et al., 2008). (Figure 1)

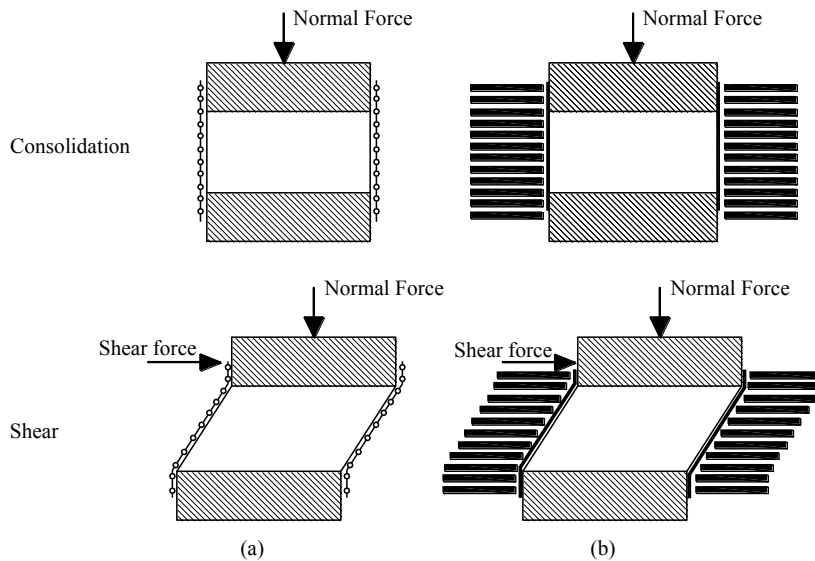
## MATERIALS AND METHODS

### Model description

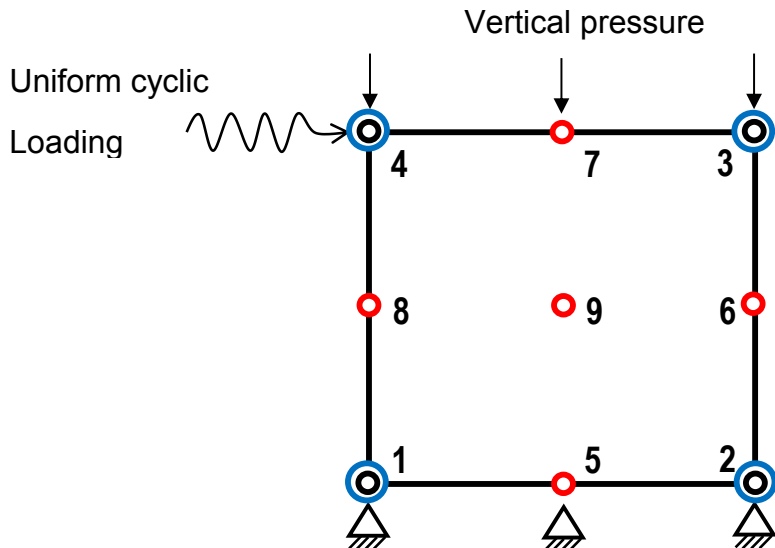
The PressureDependentMultiYield02 (PDMY2) model was used with 9-node quadrilateral finite element (Elgamal et al., 2002; Elgamal et al., 2003; Yang et al., 2003; Yang et al., 2008). PDMY2 model is an elastic-plastic material based on the multi-surface plasticity framework of Prevost (1985). The yield surfaces are of Drucker-Prager type (Drucker et al., 2013). The PDMY2 material uses a non-associative flow rule that produce the volumetric contraction or dilation response induced by shear loading. When the material is used with solid-fluid fully coupled element the contractive or dilative response causes pore water pressure changes, simulating undrained response.

9-node quadrilateral plane-strain element also called 9\_4 QuadUP element shown in Figure.2, was used to simulate SS test. The 9\_4 QuadUP element is a solid-fluid fully coupled element. Each of the four corner nodes have three degree-of-freedom (DOF), where DOF 1 and 2 represent the solid displacement in

horizontal and vertical directions, respectively, whereas DOF 3 is for the development of pore water pressure. All the interior five nodes have two DOF, representing the solid displacement in horizontal and vertical directions, respectively. The 9\_4 QuadUP element enables the model to simulate the changes in pore pressure and effective stresses of solid-fluid fully coupled material when subjected to seismic loading. The bottom nodes were fixed against horizontal and vertical oscillations. The middle and top nodes sharing same vertical position were constrained by displacement equal DOF command so that a simple shear displacement mode can be imposed. The pore water pressure DOF for the bottom nodes (node 1 and 2) is set free, which implies open drainage base for the element; however, the pore water pressure DOF for the top nodes (node 3 and 4) of the element were fixed to allow the development of pore water pressure when the element is subjected to shear stresses. The horizontal and vertical dimensions of the element were set to 0.5 m. The boundary condition of the element and the applied stresses on the element are illustrated in Figure.2.



**Figure 1:** Schematic of simple shear test (a) wired reinforced membrane (b) stack of rings (Mandokhail, 2017)



**Figure 2:** 9-4 quad up element configuration for stress-controlled cyclic simple shear simulations

### Model parameters and analysis

PDMY2 material parameters needed for calibration can be divided in to two categories. 1) Geotechnical parameters which include mass density ( $\rho$ ), small strain shear modulus ( $G_{\max}$ ), small strain bulk modulus ( $B_{\max}$ ), friction angle ( $\phi$ ), phase transformation angle ( $\phi_{PT}$ ), and initial void ratio ( $e$ ), and 2) Constitutive parameters which include contraction constants ( $ct_1$ ,  $ct_2$ , and  $ct_3$ ), dilation constants ( $dil_1$ ,  $dil_2$ , and  $dil_3$ ), and liquefaction constants ( $l_1$  and  $l_2$ ). The contraction constants represent the rate of volume decrease (contraction) in drained condition or buildup of excess pore water pressure in undrained condition during shear loading. The values of contraction constants are larger for loose sand and smaller for dense sand. The dilation constants represent the rate of volume increase (dilation) in drained case or decrease in pore water pressure in undrained case induced by shear loading. Larger values of dilation constants provide larger dilation rate and vice versa. The model parameters (both geotechnical and constitutive) are soil dependent. In this study, the model parameters were calculated for Ottawa sand, because the cyclic simple shear test measurements for Ottawa sand were available (Mandokhail et al., 2017). Ottawa sand is a standard quartz sand designated as ASTM C 778 (ASTM 1995). The Index properties of Ottawa sand is given in Table 1.

**Table 1:** Index properties of Ottawa sand (Mandokhail et al., 2017)

Soil	$G_s$	$D_{50}$ (mm)	$C_u$	$e_{\max}$	$e_{\min}$
Ottawa sand	2.65	0.31	1.89	0.764	0.49

The geotechnical parameters were calculated from the soil index properties, while the constitutive parameters were found by iteratively performing the analysis such that the SS test measurements on Ottawa sand were matched.  $G_{\max}$  was calculated from density and the shear wave velocity ( $V_s$ ) as follows:

$$G = \rho V_s^2 \quad (1)$$

$V_s$  was calculated from the empirical equation proposed by Hardin and Richart Jr (1963) as follows;

$$V_s = (91 - 44.6 \times e)(\sigma_{\text{mean}})^{0.25} \quad (2)$$

Where  $e$  is voids ratio and  $\sigma_{\text{mean}}$  is mean confining pressure.  $B_{\max}$  was calculated from shear modulus as follows:

$$B_{\max} = \frac{2G_{\max}(1 + \nu)}{3(1 + 2\nu)} \quad (3)$$

Where  $\nu$  is poisson's ratio, and was set to 0.499 to achieve  $K_0 = \nu / (1 - \nu) = 1$  condition during consolidation phase, while it was set to zero during dynamic loading phase. The constitutive parameters of the model were adjusted to fit the cyclic simple shear test results of Ottawa sand performed by Mandokhail et al. (2017). The model parameters set for Ottawa sand are given in Table 2. To provide undrained condition, the hydraulic conductivity of the element was set randomly to a value of  $1e-8$  m/s (Gingery, 2014). The

analysis were performed on loose and dense Ottawa sand with relative density ( $D_r$ ) of 40 % and 80 %, respectively, under undrained condition. The vertical stress ( $\sigma_v$ ) of 100 kPa was applied under drained elastic conditions, then uniform cyclic (sinusoidal) shear loading was applied under undrained conditions. The simulations were performed iteratively at various cyclic stress ratios. The cyclic stress ratio (CSR) is the ratio of cyclic shear stress and effective vertical stress ( $CSR = \tau_{cyc} / \sigma_v$ ). The CSR which produce liquefaction is also termed as cyclic resistance ratio (CRR).

**Table 2:** Calibrated parameters of PDMY2 model (OpenSees) for Ottawa sand

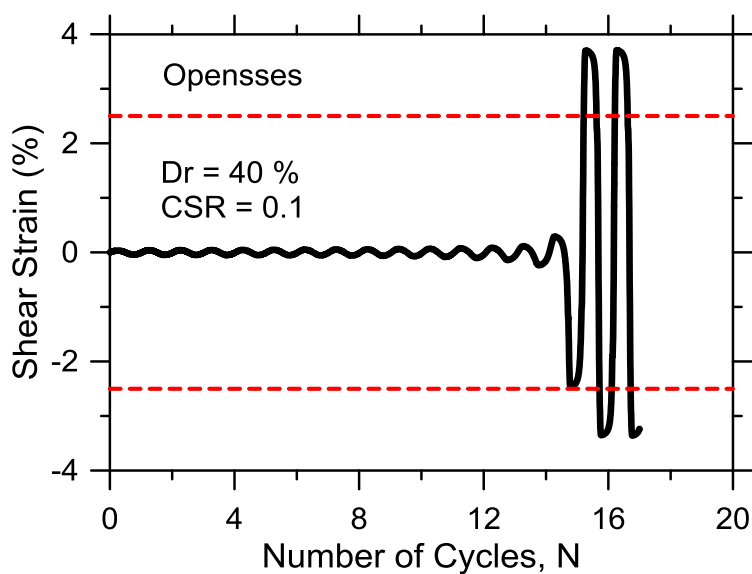
Parameters	$D_r = 40\%$	*Suggested $D_r = 40\%$	$D_r = 80\%$	Suggested $D_r = 80\%$
Friction angle $\phi$ (deg.)	32	32	36	36.5
Shear strain at failure, $\gamma_f$	0.1	0.1	0.1	0.1
Reference pressure (kPa)	101	101	101	101
Pressure dependent coefficient	0.5	0.5	0.5	0.5
Phase transformation angle, $\phi_{PT}$ (deg.)	28	26	20	26
Contraction parameter 1, $ct_1$	0.067	0.067	0.01	0.013
Contraction parameter 2, $ct_2$	5.0		5.0	
Contraction parameter 3, $ct_3$	0.2	0.23	0.0	0.0
Dilation parameter 1, $dil_1$	0.02	0.06	0.32	0.3
Dilation parameter 2, $dil_2$	2.5		2.5	
Dilation parameter 3, $dil_3$	0.2	0.27	0.0	0.0
Initial void ratio, $e$	0.66		0.55	

\* Parameters range suggested by (Mazzoni et al., 2007)

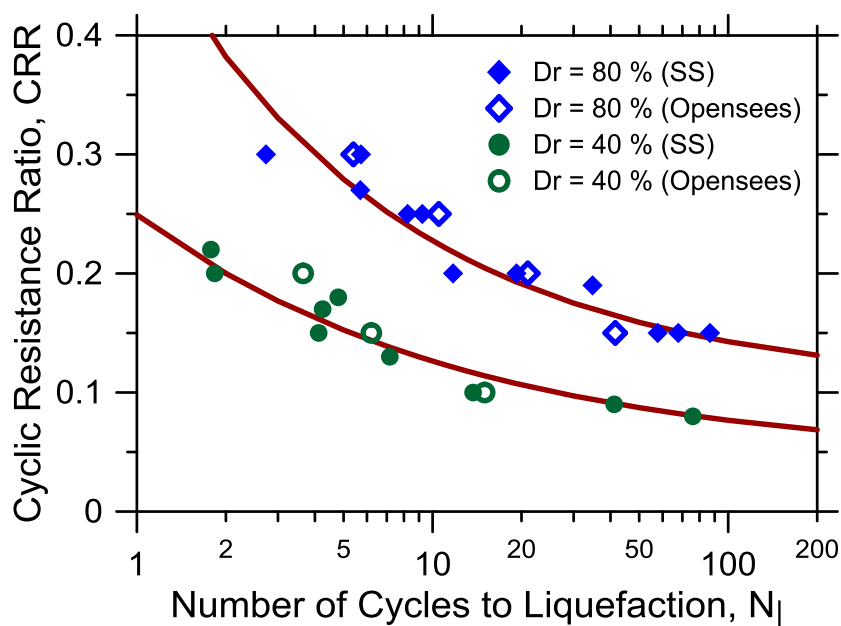
## RESULTS AND DISCUSSION

The analysis were performed on  $D_r$  40 % and 80 % under vertical stress of 100 kPa. The liquefaction resistance curve (CRR vs N curve) were calculated by plotting the CRRs versus the number of cycles (N) at which the liquefaction was triggered. Mandokhail et al., 2017 had adopted the liquefaction criteria of 5 % DA (double amplitude) shear strain. According to this criteria the sample is considered to have failed when the double amplitude shear strain is reached during the cyclic shearing. The same criteria was considered in this study for comparison purposes, as shown in Figure 3.

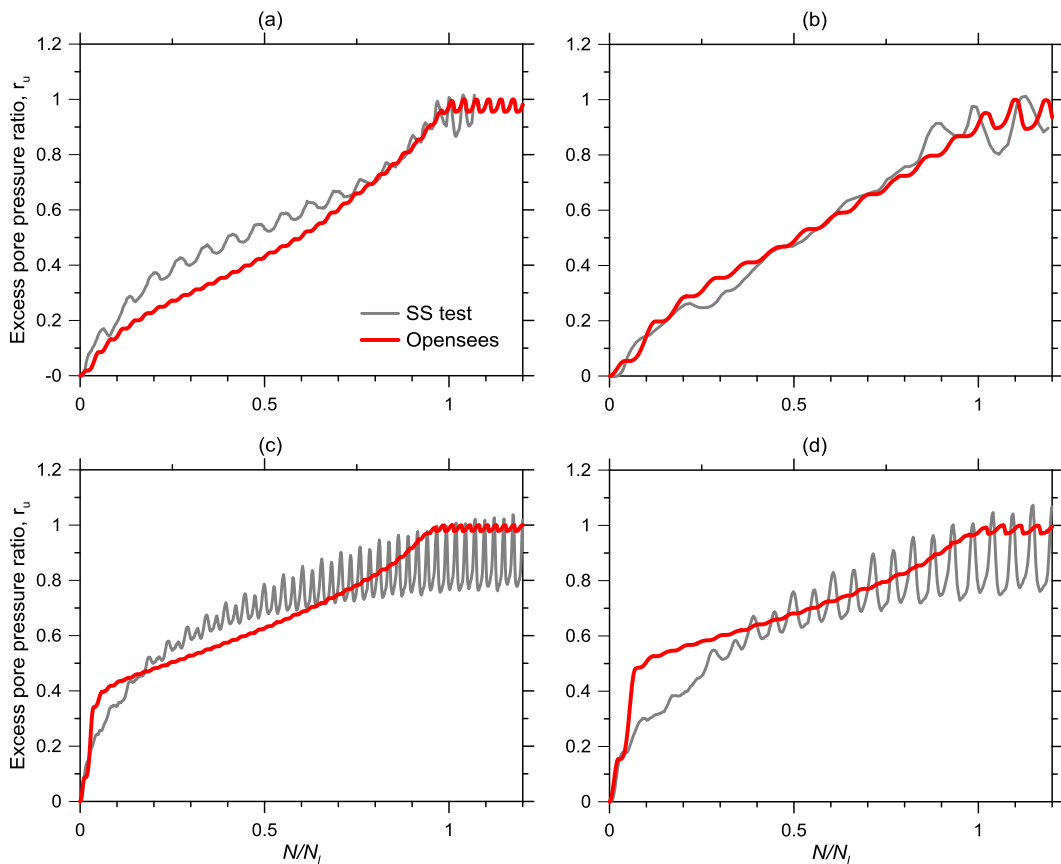
The analysis results were compared with the laboratory measurements. The liquefaction resistance measured with OpenSees for both loose and dense sands are in good agreement with the SS test measurements, as shown in Figure. 4. The excess pore water pressure ( $r_u$ ) generated due to cyclic loading is also compared with SS test measurements. The comparison show that the developed  $r_u$  in the OpenSees analysis matches well with those calculated with SS test, as shown in Figure.5. The model parameters for  $D_r = 40\%$  and  $80\%$  were also compared the range reported by Mazzoni et al., (2007), as shown in Table 2. All the parameters are within the reported range.



**Figure 3:** Cyclic shear strain obtained from OpenSees, the red dotted lines show 5% DA shear stain



**Figure 4:** Comparison of liquefaction resistance measured with OpenSees and SS test (Mandokhail et al., 2017)



**Figure 5:** Comparison of buildup of excess pore pressure in SS tests performed on Ottawa sand and OpenSees simulation (a)  $Dr = 40\%$ ,  $CSR = 0.1$  (b)  $Dr = 40\%$ ,  $CSR = 0.15$  (c)  $Dr = 80\%$ ,  $CSR = 0.2$  (d)  $Dr = 80\%$ ,  $CSR = 0.25$

## CONCLUSION

In this study, the simple shear test is modelled in the finite element program OpenSees. PDMY2 model is used with 9-node quadrilateral plane-strain element also called 9\_4\_QuadUP element. The model parameters are defined for Ottawa sand. The analysis results are compared with the laboratory measurements. The comparison has shown that the 2D model has satisfactorily captured the soil response. The liquefaction resistance and excess pore pressure measured with OpenSees are in good agreement with simple shear test measurements.

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