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EFFECT OF OVERLAP DISTANCE AND CHORD ANGLE ON PERFORMANCE OF OVERLAPPING SOIL-CEMENT COLUMNS

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ABSTRACT

The stress distribution in deep mixing improved columns is affected by cement content and in-situ soil properties of the surrounding soil. Group of cement improved soil columns can be overlapped to form a shear wall which can support side slopes of embankments to enhance stability of the supported structure. The overlap distance of these columns is one factor that influences the efficacy of the columns and their overall effect on performance of the supported structure. This paper presents a numerical investigation on the effect of overlap distance and chord angle of overlap on the performance of soil-cement columns. The analysis of results show that the total stress on the columns decreases initially from 89.9kPa to 83.1kPa at 0 and 0.16m overlap distance due to development of discontinuities and stress concentration at corners of overlapping columns. The total stress on the column also increases between 0.16 and 0.32m overlaps corresponding to e/d ratio of 0.2 to 0.4m. This implies that values between 0.2-0.4 can be adopted for ratio of overlap distance and column diameter in design of overlapping column.

Key words: Weak soil, deep mixing, soil-cement, overlapping columns, overlap distance, total stress.

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1. INTRODUCTION

Soil improvement becomes very necessary when the present state of a soil in terms of its engineering properties fails to meet the proposed use of the site. Deep soil mixing techniques have been designed to address the problems associated with performance of weak engineering soils due to poor resistance of these soils to shear deformation, low bearing capacity and excessive vertical compression, (Shakriet al., 2014). Undoubtedly, Cement-Soil mixing technique has been widely employed in the construction field for strength enhancement and improved compressibility, (Abbey, et al., (2015); Abbey et al., (2016); Farouk and Shahien(2013); Gaafer, et al., (2015); Liu and Lee (2016)). The strength of Portland cement (PC) stabilised soils are usually high, making PC the most commonly used binder in soil improvement, (Holm, Terashi, 2003, Consoli et al. 2015,Oana, 2016). Chen, et al., (2016) and Asturias and Lorenzo (2015) examined the variation in strength of marine clay, improved with cement during a wet deep mixing work at the Marina Bay Financial Centre. According to Chen, et al., (2016) strength distribution in deep mixing improved columns is affected by cement content and in-situ soil properties. Cement deep mixing columns have been used to reduce settlement of embankments due to cementation effect. A full scale study conducted by Bergado et al., (2005) on embankment loading on soil-cement columns of 0.5m diameter and 9m long placed at1.5m centre to centre spacing showed that after one year of monitoring, the settlement of the soft clay under embankment loading has reduced by about 70%.Paulo, et al., (2011), revealed that the application of soil-cement columns in strengthening of foundation of embankment structures reduces settlement and small differential settlement. Sari et al. (2009) adopted a finite element modelling approach to study the consolidation behaviour of an embankment supported by multi columns of cement-fly ash- gravel, soil-cement and lime. The result of their analysis showed that soft ground treated with multi-columns can reasonably reduce total and differential settlement and restricts lateral movement of the supported embankment, thereby increasing stability.

Song-Yu et al., (2012) reported that T-shaped deep mixed columns can withstand more stress than conventional deep mixed columns. They also, stated that the conventional deep mixed column exhibits higher stress concentration ratio than the T-shaped deep mixed column supported ground but T-shaped deep mixed column supported ground have higher efficacy than conventional deep mixed column. Deep mixing improved soils can be used as soil columns to support embankment loading either as group of columns under central portion of the embankment or as overlapping columns under side slope of embankments. In design of deep mixing columns to support embankment loading, it is expected that trial geometry of the columns be carried out. This geometry should be able to safely support the imposed load without excessive deformation or instability of the system. During this process, a general layout of the supposed embankment and the deep mixing improved zone are considered and geometric parameters such as column spacing, e/d ratio, chord angle and replacement ratios are defined. The e/d is the ratio of column overlap distance (e) to diameter of the column (d). According to the US Federal Highway Design Manual (2013), group of cement improved soil columns can be overlapped to form a shear wall as shown in Figure 1. Yang et al. (2011) reported that overlapping soil–cement columns should be employed in improving the stability of excavations rather than tangential columns. Paulo, et al., (2011), carried out a numerical analysis study on an embankment built on a normally consolidated soft soil reinforced with soil-cement columns using a coupled soil-water formulation. Sari et al. (2009) modelled the embankment fill and the surrounding soil as linear elastic-perfectly plastic materials with the Mohr-Coulomb failure criterion and the multi-columns as linear elastic materials. They adopted the modified Cam Clay model and used the Biot's consolidation theory to simulate the soil behaviour using two dimensional FE code developed at the University of Coimbra and the deep mixed column (DMC) was modelled using linear elastic laws with parameters based on laboratory results. Kitazume (2009) reported that linear elastic laws do not allow yielding of top of the DMC to be simulated due to low confining stress and high loads, and the failure due to bending caused by horizontal movement of the column that may occur at the columns founded under the toe of the embankments. But, Abusharar, et al., (2009), stated that linear elastic model could be adopted because the reduction in strength properties using safety factors causes stress level to be considerably lower than the yielding stress of the DMC material. However, these studies have not considered the effect of ratio of overlap distance to column diameter (e/d) on stability of overlapping DMC. Therefore, this present study has been conducted to investigate the effect of e/d ratio on performance of overlapping soil columns using finite element analysis (FEA).

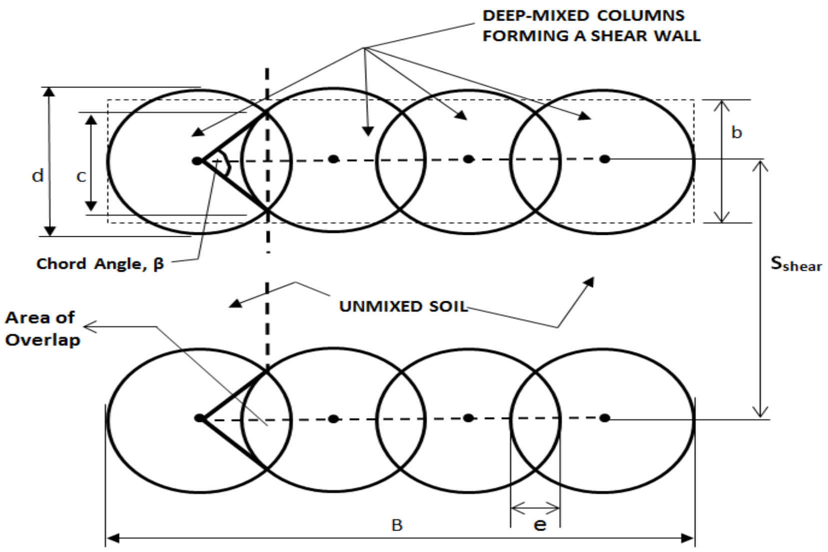

Figure 1 Overlapping deep mixed columns forming a shear wall, (FHWDM, 2013).

2. METHODOLOGY

2.1. Experimental work

The investigated soil was first subjected to preliminary laboratory test such as the Atterberg limit test as shown in Table 1.0, based on the procedures outlined in British Standard (BS 1377-2:1990). In preparing the samples of improved soil, the soil was mixed with 20% cement content by weight of dry soil at water to cement ratio of 1:1 for 10-15min to make a uniform mixture. Immediately after mixing, improved soil was placed into cylindrical tubes of 37mm in diameter and 150mm in height in stages and in each stage, the cylinder was tapped several times against a hard surface to ensure removal of any air bubble trapped within the samples. To ensure that equal degree of compaction at saturation was achieved for all mixed samples, a dead weight of 10kg was placed on the mixed samples in the cylindrical tubes before extraction. The improved sample was then cured under water up to 56 days and subjected to triaxial test at confining pressures of 70kPa and 100kPa to obtain relevant input parameters for the numerical modelling.

Table 1 Soil classification parameters of unimproved weak soils

Soil property	Moisture content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Unit weight (kN/m^3)	Specific gravity	Classification
Symbol	w	ω_l	ω_p	I_p	γ	G	BSCS
Value	61.0	87.0	42.3	44.7	22.5	2.5	MH

2.2. Numerical modelling

The numerical study consisted of a model block of overlapping columns placed at different overlapping distances. The modelling and analysis of the deep mixed soil - weak soil system was carried out using the available commercial FEA based software (Midas GTS NX), capable of analysing stress distributions within the system of overlapping columns taking into account the nonlinear elastic behaviour of the improved material under large vertical displacement of about 50mm. According to Ignat et al. (2015), modelling a large number of overlapping circular columns results to large number of elements, and this creates problem of longer time of time of Analysis. In order to eliminate this problem, four overlapping soil columns of equal diameter (0.8m) were modelled as cylindrical solid elements surrounded with a 3D model of rectangular block of weak soil and full interaction between the columns and the weak soil was assumed. The material properties were obtained from results of undrained triaxial test on soil-cement improved material of the soil with properties previously shown in Table 1, except the adopted values of elastic modulus and poison ratio which were based on existing studies (Ignat et al. 2015, Jiang, 2013, Guanbao et al. 2016). Details of the adopted geometric, material properties and constitutive model are shown in Table 2.0.

Table 2 Geometric and material properties

Geometry						
Model number		1	2	3	4	5
e/d ratio		0	0.2	0.4	0.5	0.6
Diameter of column (m)		0.8	0.8	0.8	0.8	0.8
Height of column (m)		3	3	3	3	3
Number of column		4	4	4	4	4
Material property						
Material	Model type	E(MPa)	ν	γ(kN/m^3)	ϕ (°)	c (kPa)
Silt	MC	2	0.35	22.5	15	12
DM column	DP	10	0.3	20	20	200

MC = Mohr Coulomb; DP = Drucker Prager; E = Young's modulus; γ = Weight density; ν = Poison's ratio; ϕ = Angle of shear resistance; c = cohesion

The numerical analysis considered geometric non-linearity based on mechanical response of the improved soil columns under large vertical displacement (50mm). The two nonlinear elastic models adopted were the Mohr coulomb and Drucker Prager models because these models are capable of defining and can predict real soil behaviour (Sari et al. 2009). According to Sandhya et al., (2014), the Drucker-Prager model can accurately predict greater strength of soils at lower deformation compared to the Mohr- Coulomb model, which predicts lower strength at greater strains at all stages of loading. The weak soil was modelled using Mohr coulomb model while the DMC was modelled with the Drucker-Prager model. The boundary conditions were such that, the bottom boundary of the weak soil – column system was assumed fixed and the vertical boundaries were restricted against horizontal movement but vertical movement allowed and this corresponds to the auto boundary condition function on Midas GTS NX. To fully understand the behaviour of the overlapping columns, it was assumed that only the improved overlapping columns support the load and therefore, the displacement was applied on the face of the soil columns.

3. ANALYSIS AND DISCUSSION

The FHWDM, (2013) outlined general procedure for establishment of area replacement ratio of columns beneath the central portion and side slopes of embankments by providing certain range of values of e/d ratio as shown in Table 3.0. This may imply carrying out trial calculations using various e/d ratios to ascertain acceptable settlements and stability of the embankment based on performance of the supporting soil columns. To investigate suitable values of e/d ratio for design of overlapping columns for embankment side slopes, different geometric configurations in terms of e/d ratios were investigated for four overlapping columns of equal diameters of 0.8m surrounded by a rectangular block of soil with properties shown in Table 1.0 and Table 2.0 respectively.

Table 3 Recommended values of ratio of chord length of overlap to centre-to-centre spacing of shear wall, FHWD manual, (2013).

$\frac{e}{d}$	$\frac{c}{S_{shear}}$				
	$\frac{d}{S_{shear}} = 0.1$	$\frac{d}{S_{shear}} = 0.2$	$\frac{d}{S_{shear}} = 0.3$	$\frac{d}{S_{shear}} = 0.4$	$\frac{d}{S_{shear}} = 0.5$
0	0.000	0.000	0.000	0.000	0.000
0.1	0.044	0.087	0.131	0.174	0.218
0.2	0.060	0.120	0.180	0.240	0.300
0.3	0.071	0.143	0.214	0.286	0.357
0.4	0.080	0.160	0.240	0.320	0.400
0.5	0.087	0.173	0.260	0.346	0.433

Perfect bonding and zero slippage was assumed between surrounding soil and overlapping columns. The meshing was carried out such that all nodes were connected between the improved and natural soil system as shown in Figure 2. The columns with e/d =0 were space at 1.2m centre to centre.

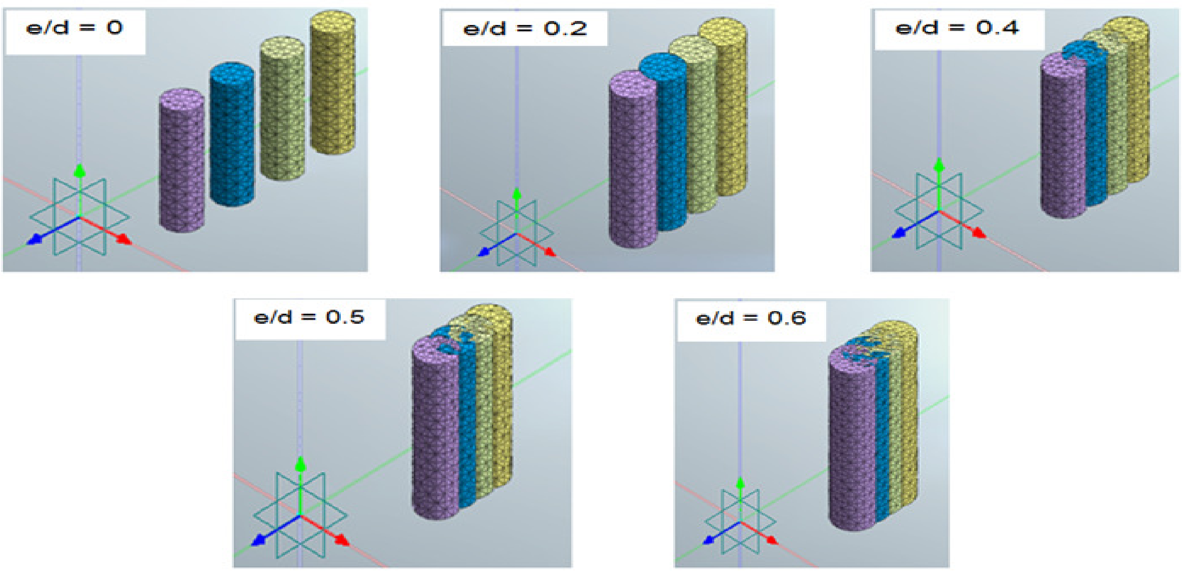

Figure 2 Meshed soil-cement columns for different e/d ratios

An ultimate limit state vertical displacement of 50mm was then applied on faces of the overlapping columns and a nonlinear elastic analysis was conducted to establish the effect of e/d ratio and chord angle of overlap on performance of overlapping columns in terms of total stress as presented in Table 4.0.

Table 4 Stresses on overlapping and group deep mixing columns

c-c spacing of columns (m)	Diameter of column, d (m)	Overlap distance, e (m)	e/d ratio	Chord angle in (Radian)	Stress S-XX (kPa)	Stress S-YY (kPa)	Stress S-ZZ (kPa)
1.2	0.8	0	0	0	81.8	81.2	89.9
0.7	0.8	0.16	0.2	1.287	68.9	70.7	83.1
0.5	0.8	0.32	0.4	1.855	72.3	73.8	84.8
0.4	0.8	0.4	0.5	2.095	72.4	69.4	83.7
0.3	0.8	0.5	0.6	2.319	68.4	61.4	78.7

Chord angle in radian, β= 2arc $\cos(1-\frac{e}{d})$Eqn. 6.1

Figure 3.0 and Figure 4.0 show the effect of overlap distance, e/d ratio and chord angle of overlap on total stress on the overlapping columns of 0.8m diameter. From Figure 3.0, it is clear that the total stress (TS-ZZ) on the columns decreases initially from 89.9kPa to 83.1kPa at 0 and 0.16m overlap distance due to development of discontinuities and stress concentration at corners of overlapping columns as shown in Figure 5.0. From Figure 3.0, the total stress (TS-XX, TS-YY and TS-ZZ) increases between 0.16 and 0.32m overlaps corresponding to e/d ratio of 0.2 to 0.4m in Figure 4.0

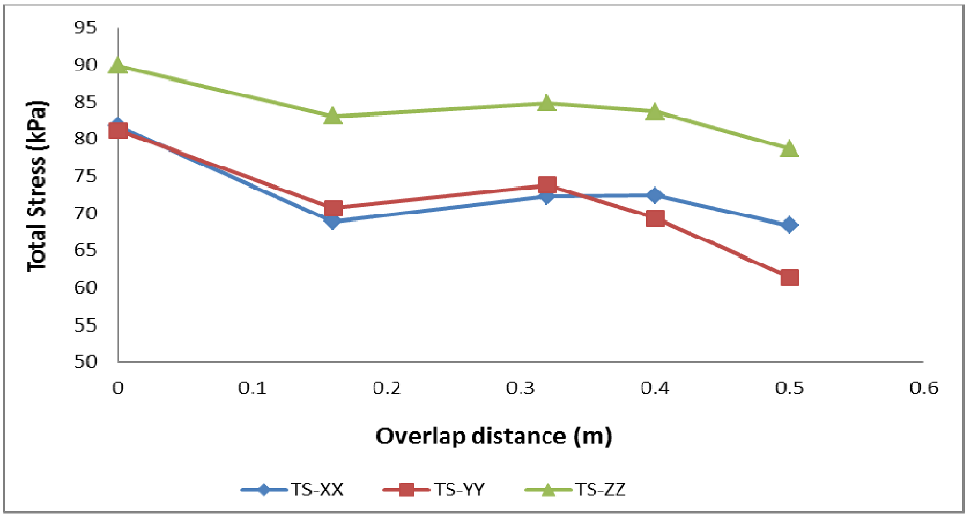

Figure 3 Variation of total stresses with column overlap distance

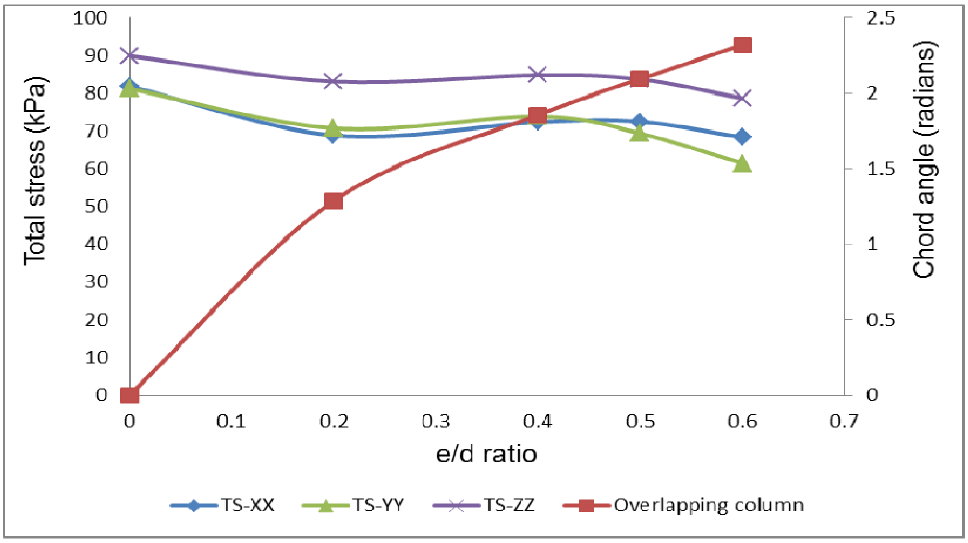

Figure 4 Variation of total stress with e/d ratio and column chord angle (radians)

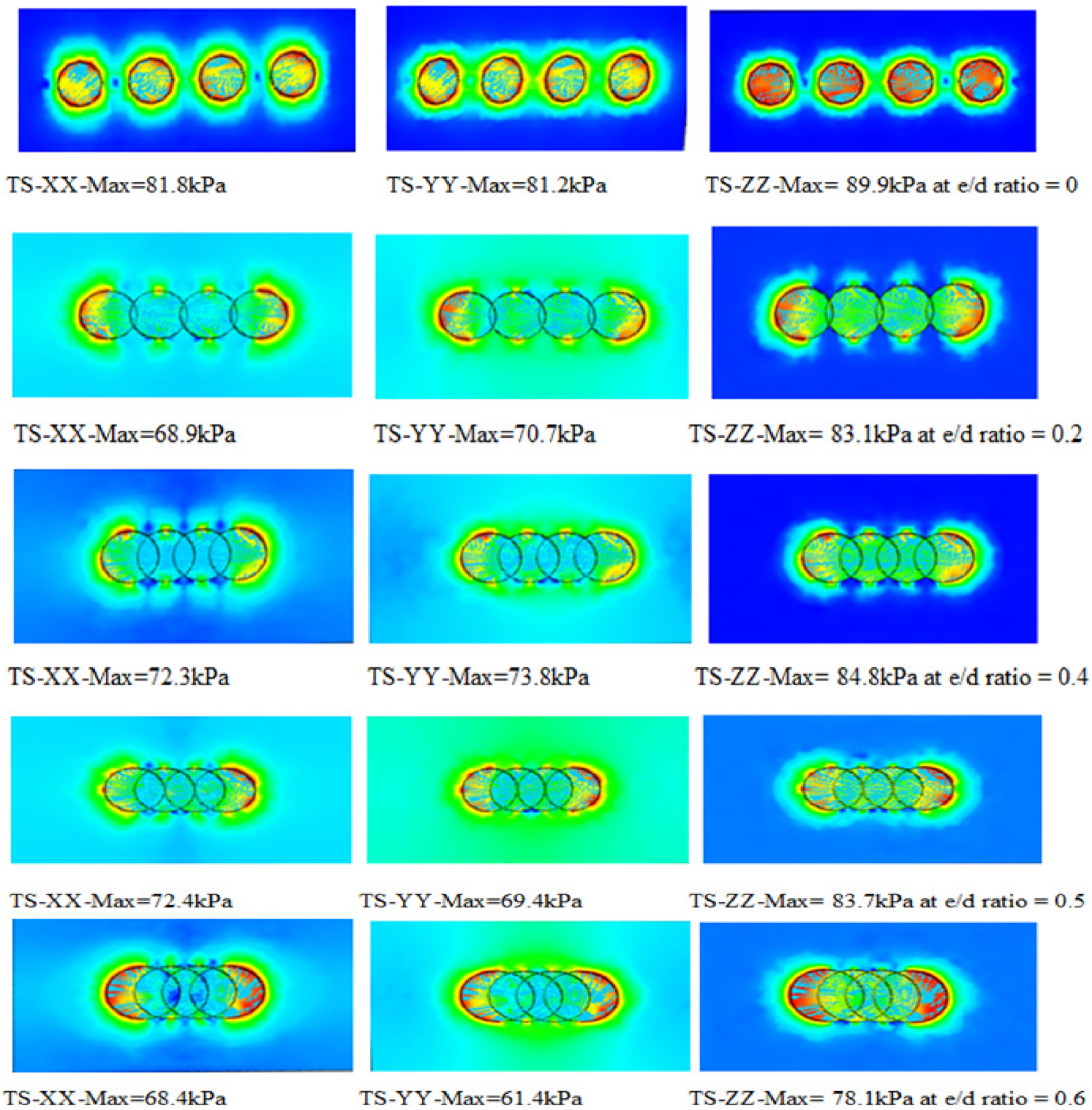

Figure 5 Stress contours of group and overlapping columns in plan

The increase in total stress shows that for e/d ratio between 0.2 to 0.4m the stress distributions within the overlapping columns is widely spread with lower stress concentration at the corners and hence, increase in total stress. However, beyond 0.32m overlap distance (say at e/d = 0.4), the total stress decreases due to higher stress concentration at the corners of overlap. It is clear from Figure 4.0 that the stress increase corresponds to increase in chord angle of overlap. Based on the mathematical relationship between chord angle and area replacement ratio as shown in Eqn. 4.0, it can be said that the increase in total stress of overlapping columns with e/d of 0.2 to 0.4, can also be attributed to increase in area replacement ratio ($a_{s,shear}$) of the overlapping columns as shown in Figure 6.0, due to increase in chord angle of overlap from 1.2287rad to 1.855rad.

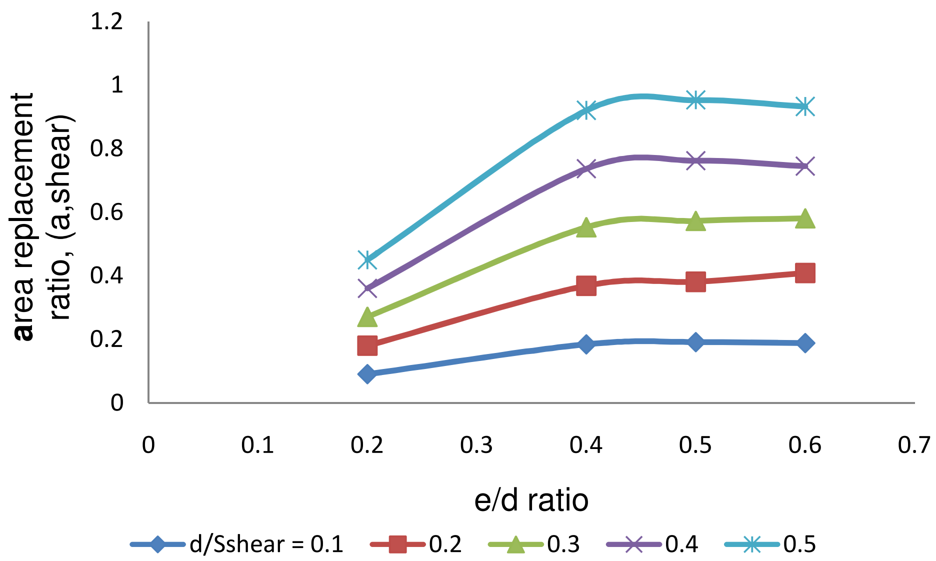

Figure 6 Effect of e/d ratio on area replacement ratio

$$\frac{c}{S_{shear}} = \frac{2a_{s,shear} \cdot \sin(\beta)}{\pi - \beta + \sin(\beta)} \tag{2}$$

$$a_{s,shear} = \frac{c(\pi-\beta+\sin(\beta))}{2S_{shear} \cdot \sin(\beta)} \tag{3}$$

or

$$a_{s,shear} = \frac{0.5c}{S_{shear}} \cdot \frac{(\pi-\beta+\sin(\beta))}{\sin(\beta)} \tag{4}$$

Where $\frac{\mathbf{c}}{\mathbf{S_{shear}}}$ $= \boldsymbol{ratio\ of\ chord\ length\ to\ shear\ wall\ spacing}$

From Eqn. 6.4, for β = 1.287rad($\frac{\mathbf{e}}{\mathbf{d}} = \mathbf{0.2}$), $a_{s,shear} = \frac{1.5c}{S_{shear}}$ (5)

and for β = 1.855rad ($\frac{e}{d} = \mathbf{0.4}$), $a_{s,shear} = \frac{2.3c}{S_{shear}}$ (6)

From Eqn. 5.0 and 6.0, an increase in $\frac{e}{d}$ from 0.2 to 0.4 (i.e. β of 1.287 to 1.855) increases the coefficient of $\frac{c}{S_{shear}}$ from 1.5 to 2.3, corresponding to increase in $a_{s,shear}$.

However, for β = 2.095rad and $\frac{e}{d} = \mathbf{0.5} > 0.4$, $a_{s,shear} = \frac{2.2c}{S_{shear}}$ (7)

Similarly, for β = 2.319rad and $\frac{e}{d} = \mathbf{0.6} > 0.4$, $a_{s,shear} = \frac{2c}{S_{shear}}$ (8)

Equation 7.0 and 8.0, have shown that increase in $\frac{e}{d} > 0.4$ (i.e. β of 2.095 to 2.319) causes reduction in coefficient of $\frac{c}{S_{shear}}$ from 2.3 to 2.2 and 2 respectively and hence, reduction in $a_{s,shear}$. To further explain the effect of $\frac{e}{d}$ ratio on area replacement ratio, typical values of ratio of chord length to centre-to-centre spacing of shear wall ($\frac{c}{S_{shear}}$)as shown in Table 5.0 where used to calculate area replacement ratios using Eqn. 5.0 to 8.0.

The $\frac{c}{S_{shear}}$ values for $\frac{e}{d}$ of 0.6 in Table 5.0were calculated by extrapolating for each value of $\frac{d}{S_{shear}}$ (ratio of column diameter to centre-to-centre spacing).

Table 5 Variation of area replacement ratio with $\frac{e}{d}$ratio

$\frac{e}{d} = 0.2$			$\frac{e}{d} = 0.4$			$\frac{e}{d} = 0.5$			$\frac{e}{d} = 0.6$		
$\frac{d}{S_{shear}}$	$\frac{c}{S_{shear}}$	$a_{s,shear}$	$\frac{d}{S_{shear}}$	$\frac{c}{S_{shear}}$	$a_{s,shear}$	$\frac{d}{S_{shear}}$	$\frac{c}{S_{shear}}$	$a_{s,shear}$	$\frac{d}{S_{shear}}$	$\frac{c}{S_{shear}}$	$a_{s,shear}$
0.1	0.060	0.090	0.1	0.080	0.184	0.1	0.087	0.191	0.1	0.094	0.190
0.2	0.120	0.180	0.2	0.160	0.368	0.2	0.173	0.381	0.2	0.204	0.408
0.3	0.180	0.270	0.3	0.240	0.552	0.3	0.260	0.572	0.3	0.290	0.580
0.4	0.240	0.360	0.4	0.320	0.736	0.4	0.346	0.761	0.4	0.372	0.744
0.5	0.300	0.450	0.5	0.400	0.920	0.5	0.433	0.953	0.5	0.466	0.932

The FHWD manual, (2013) recommends e/d ratio between 0.2 to 0.35 for design of overlapping columns however, this study has shown that e/d ratio between 0.2 – 0.4 can also be used for design of overlapping columns due to increase in area replacement ratio compared to area replacement ratio values for $\frac{e}{d} > 4$at different $\frac{d}{S_{shear}}$ values as previously shown in Figure 6.0. This study has shown that area replacement ratio is influenced by ratio of column overlap distance to diameter ($\frac{e}{d}$)and ratio of $\frac{c}{S_{shear}}$ respectively. An increase in area replacement ratio due to increase in $\frac{e}{d}$ratiocanreduce the bearing pressure at the base of overlapping block of columns according to Eqn. 9.0 and 10.0, and this is important in terms of bearing capacity failure. Since total bearing pressure at the toe of overlapping columns is expected to be less than some allowable values.

$q_{toe} = \frac{N}{B}\left(\frac{2B}{3x_N a_{s,shear}} - \frac{1}{a_{s,shear}} + 1\right)$ for $x_N \leq \frac{B}{3}$ (9)

$$q_{toe} = \frac{N}{B}\left(\frac{3}{a_{s,shear}} - \frac{6x_N}{Ba_{s,shear}} + 1\right) \text{for} \frac{B}{3} \leq x_N \leq \frac{B}{2} \quad (10)$$

Where; N = Resultant vertical force on the overlapping column

x_N = Location of resultant force

B = Length of wall formed by overlap

From Eqn. 9.0 and Eqn. 10.0, any increase in area replacement ratio, $a_{s,shear}$ as a denominator in both equations will reduce the LHS of the equation.

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