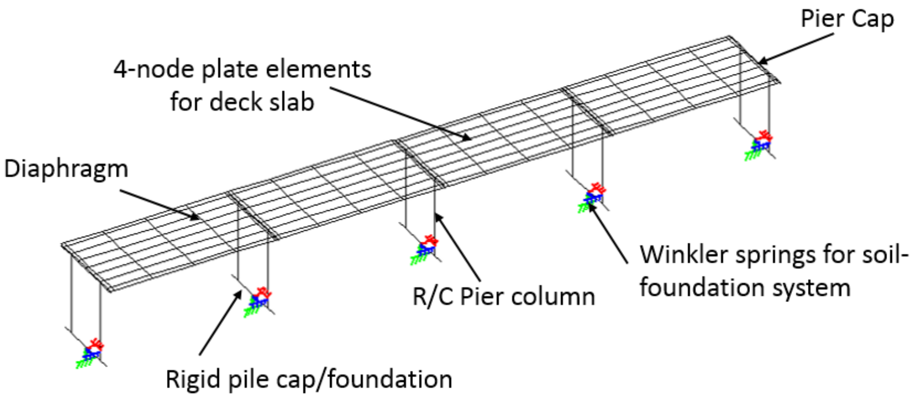

Fig. 3. 3D FEM model of the bridge

Table 3: Ground motions used in the study

	EQ Record ID	**Seismic event**	**Year**	**Station**	**Mag.**	**PGA (g)**	**Fault dist. (km)**	**V_s (m/s)**
Design Basis Earthquake	1	Edgecomb, NZ	1987	Maraenui Primary School	6.6	0.036	69	425
	2	Irpinia- Italy	1980	Calitri	6.9	0.14	17	600
	3	Chi-Chi-Taiwan	1999	CHY015	7.6	0.183	38.1	229
	4	Spitak-Armenia	1988	Gukasian	6.77	0.205	24	275
	5	Kobe- Japan	1995	Shin Osaka	6.9	0.21	19	256
	6	Kocaeli, Turkey	1999	Ambarli	7.51	0.23	69.6	175
Functional Evaluation Earthquake	7	San Fernando	1971	Castaic - Old Ridge Route	6.61	0.266	23	450
	8	Landers	1992	Joshua Tree	7.28	0.28	11	379
	9	Dinar, Turkey	1995	Dinar	6.4	0.30	3.4	220
	10	Tabas, Iran	1978	Dayhook	7.35	0.328	13.9	660
	11	Imperial Valley	1940	Elcentro	6.9	0.36	17	310
	12	Loma Prieta	1989	Gilroy Array #2	6.93	0.40	11	271
Max. Considered EQ	13	Northridge-01	1994	Beverly Hills	6.69	0.43	17	356
	14	Duzce, Turkey	1999	Duzce	7.14	0.52	6.6	276
	15	Kobe, Japan	1995	Takatori	6.9	0.64	1.5	256

3. RESULTS & DISCUSSION

As mentioned earlier that three response parameters were investigated in the study i.e. bridge deck acceleration, longitudinal displacement of deck and seismic shear force for 180 cases of FEM analysis. Due to space limitation, only results and discussion of seismic shear force are presented herein.

3.1 Variation of seismic shear force

3.1.1 Elastic pier column

Fig. 4 presents the variation of computed maximum seismic shear force in one column of the bridge pier for various boundary / soil conditions as a function of PGA. The computed column shear force showed an increasing relationship with PGA. However, the maximum variation of the column shear force for a particular seismic ground motion across various boundary / soil conditions was -20% and +40%. Negative values indicate a reduction in column shear force as compared to the fixed base case. Sudden upward and downwards jumps in computed column shear force values for EQ records 5 and 10 respectively, can be attributed to the characteristics of these earthquakes.

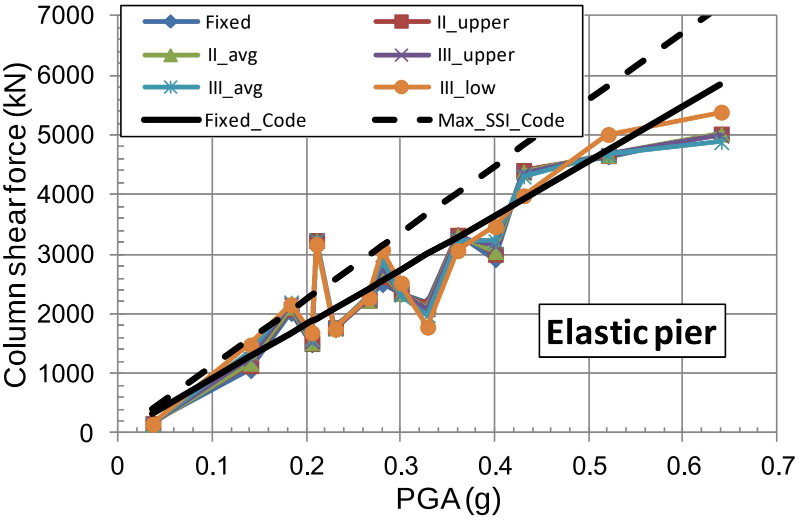

Fig. 4: Variation of seismic shear force as a function of PGA – Elastic pier column

Code based seismic shear force for the fixed base case (which will give the lower bound value) and for the SSI case with maximum column shear force (i.e. III_upper) are also plotted in these figures. It can be noted that the code based values of column shear provide a reasonable bound for the computed values of column shear from FEM analyses.

3.1.2 Inelastic pier column

Maximum seismic column shear force computed from FEM analyses for the bridge with inelastic pier columns is plotted in Fig. 5 for various cases of boundary / soil conditions for the considered seismic input motions.

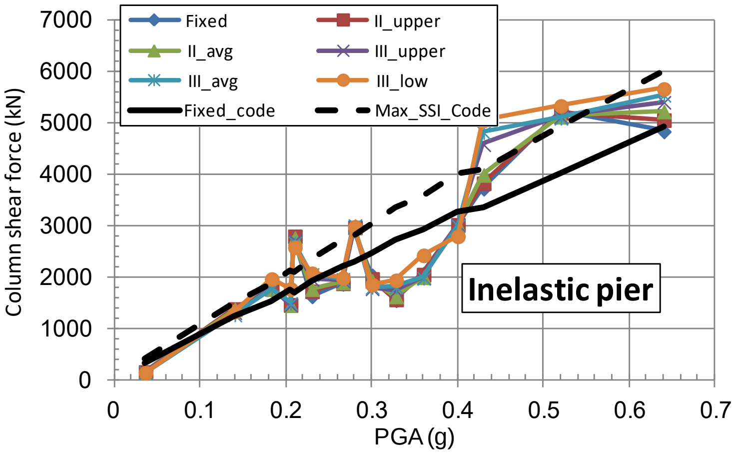

Fig. 5: Variation of seismic shear force as a function of PGA – Inelastic pier column

It can be noted that the column

shear force shows a linearly increasing trend between PGA of 0.03 and 0.3g. Then a dip is noted between 0.3g and 0.4g. Beyond 0.4g, a sudden increase in column shear force and then a flatter increase beyond 0.4g in seismic column shear force can be observed. The sharp increase in the column shear force beyond PGA of 0.4g can be attributed to the bridge pier column design which is designed for a seismic acceleration of 0.2g as well as the characteristics of the seismic ground motions which interacted favorably with the bridge dynamics to produce large seismic shear forces. Yet another factor is the fact that the column rebars has started to yield for seismic motions greater than 0.4g and the large displacements created larger seismic shear force in the pier columns. It is to be recalled that the bridge is designed for a PGA of 0.2g and yielding of rebars in the pier columns is expected for PGA greater than 0.4g.

Maximum scatter of seismic shear force in a column for a particular earthquake for various conditions of soil profile is -12% and 38%.

3.2 Effect of SSI on seismic column shear force

<u>3.2.1 Elastic pier column</u>

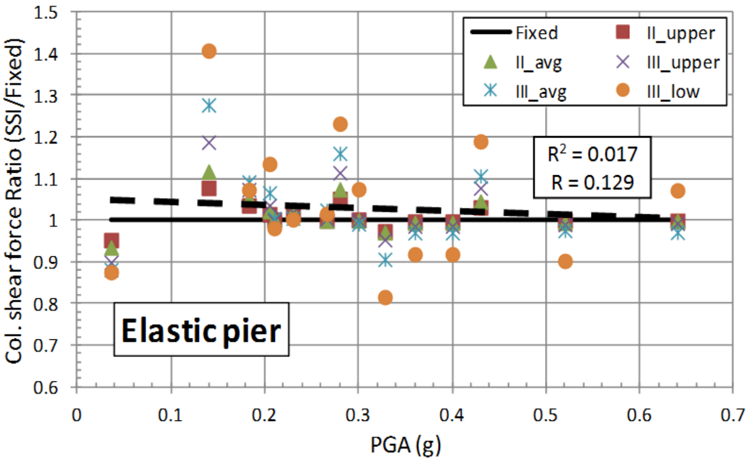

Fig. 6: Column shear force ratio between SSI and fixed base cases plotted against PGA – Elastic pier column

Fig. 6 presents the column seismic shear force ratio between the SSI cases and the fixed base case for bridge with elastic pier columns. A ratio of more than 1 is indicative of increase in column shear force due to inclusion of SSI. The column shear force ratio varies between 0.8 and 1.4 for the bridge with elastic pier columns which means that column shear force is increased as well as decreased for certain seismic ground motions by including SSI. Inclusion of SSI seems to be beneficial in 5 ground motions (i.e. ratio < 1.0) and detrimental in 10 (i.e. ratio > 1.0).

An almost equal scatter above and below the unit value can be observed and a trend of this ratio with respect to PGA is difficult to ascertain. This observation is supported by a *R* value of 0.13 for the linear regression line plotted for the data in Fig. 6. This low *R* value indicates that there is no correlation between the column shear force ratio and PGA (Devore & Farnum, 2005).

<u>3.2.2 Inelastic pier column</u>

Effect of SSI on seismic shear force in the pier column as compared to the fixed base case for the bridge with inelastic pier columns is determined through the ratio of column shear force for bridge model including SSI to that for the fixed base case (i.e.

without SSI). The results are plotted in Fig. 7. A value of more than one for this ratio indicates that the column shear force increases due to inclusion of SSI. It can be noted in Fig. 7 that the displacement ratio is more than unity for all but six earthquake records which implies that inclusion of SSI generally results in increased seismic shear force in the pier columns as compared to the fixed base case. The column shear force ratio varies between 0.86 and 1.38.

A linear regression line plotted for the data in Fig. 7 gives a R^2 value of 0.121 and a R value of 0.348 which indicates a weak correlation between PGA and displacement ratio (Devore & Farnum, 2005). Recall that a linear regression resulted in no correlation between these parameters for the elastic pier column case.

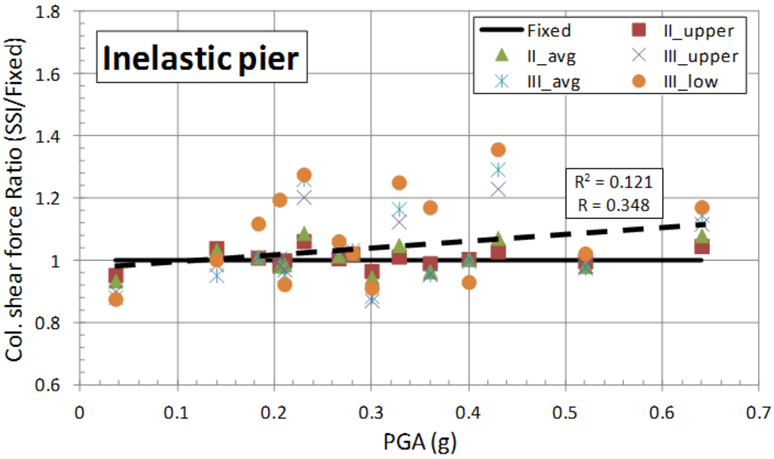

Fig. 7: Column shear force ratio between SSI and fixed base cases plotted against PGA – Inelastic pier column

3.3 Effect of pier column non-linearity on seismic shear force in pier columns

In order to delineate the impact of pier column non-linearity on seismic column shear force, the ratio of column shear force for inelastic and elastic pier column cases are plotted in Fig. 8 as a function of PGA for the considered cases of bridge boundary condition / soil conditions and seismic ground motions.

A value of the column shear ratio of more than 1 indicates that pier column inelasticity results in increased column shear force as compared to the bridge with elastic pier columns. The shear force ratio varies between 0.6 and 1.27 for all the cases. The shear force ratio is more than 1 for 30 data points, less than unity for 54 and equal to unity for 6 data points. This implies that inclusion of pier column non-linearity decreased seismic shear force in the columns for 60% of the data points and increased it in 33%, while it stayed the same for 7% of the data points. If the same statistics are computed for PGA up to 0.4g, then pier non-

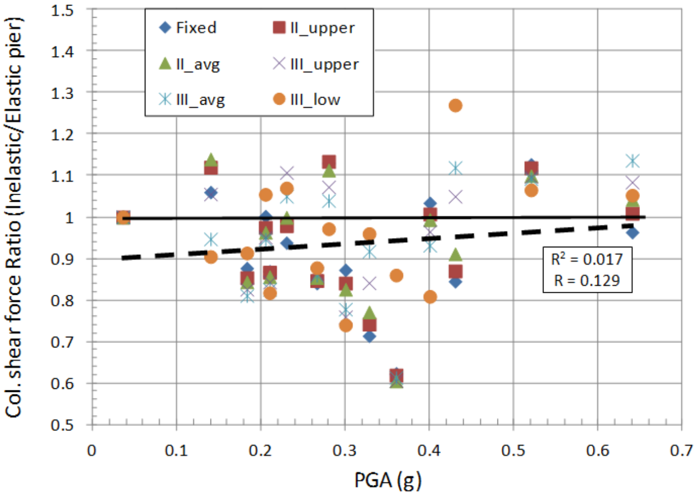

Fig. 8: Column shear force ratio for inelastic and elastic pier as a function of PGA

linearity led to decrease in seismic shear force in 50 data points which is 70% of the total data points up to PGA of 0.4g. It can therefore, be concluded that inclusion of pier inelasticity generally results in decreased seismic shear demand on the pier columns for design level earthquakes.

A linear regression of the data yielded $R^2 = 0.017$ and $R = 0.129$ as plotted in Fig. 8. This value of R represents no correlation between PGA and the column shear force ratio between inelastic pier column cases and elastic pier column cases (Devore & Farnum, 2005).

4. CONCLUSIONS

SSI effects can be neglected for soils II_upper and II_avg while computing seismic shear force in bridge piers. On the other hand, pier column non-linearity cannot be ignored for any boundary conditions. SSI and pier column non-linearity mostly reduced the seismic shear forces as compared to the fixed base and elastic pier cases.

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