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Reliability of Caltrans SDC Criterion for Neglecting the P-Delta Effects for RC Bridge Columns

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Abstract

P–Delta effects can cause a significant reduction in both the shear capacity and initial stiffness of columns and needs to be properly addressed in the design. The random nature of ground motion, such as variability in intensity, frequency content, and duration, contributes to the structural response's uncertainty. Caltrans SDC introduces a method for finding a safe threshold for neglecting the P-Delta effects. This research intends to investigate the reliability of reaching the target damage level introduced by the Caltrans SDC under seismic loading through studying the response of a group of RC bridge columns. A group of 26 columns that comply with the Caltrans SDC criterion to neglect the P-Delta effects have been subjected to the Far-Field earthquake record set collected from the PEER-NGA database. The design target ductility recommended by the Caltrans SDC is compared with the maximum obtained ductility.

Keywords - *Caltrans SDC, Neglecting the P-Delta effects, Nonlinear time history analysis, Aleatory uncertainties*

I. INTRODUCTION

Uncertainty is defined as the knowledge gap between what is known and what needs to be known to make an optimal decision [1]. In studying RC bridge columns' structural response columns, sources of uncertainty can be categorized into aleatory and epistemic uncertainties [2]. The aleatory uncertainty (originating from the Latin aletor, meaning the dice thrower) results from the random nature of ground motions. The variability in characteristics of ground motion records such as intensity, frequency content, and duration is the main contributor to the aleatory uncertainties. Epistemic uncertainties (originating from the Latin episteme, meaning knowledge) are caused by the inability to incorporate all factors contributing to lateral strength and stiffness in the structural model.

P–Delta effects result from gravity loads acting through the structure's lateral displacement, which is typically induced due to earthquake, wind, or explosion [3]. P-Delta effects create a pernicious cycle that progressively increases the lateral displacement and might trigger instability [4], [5], [6].

P-Delta effects can cause a significant reduction of both the shear capacity and initial stiffness of RC bridge columns and unfavorably impact its seismic response. It is important to reliably detect the safe threshold for ignoring the P-Delta effects [7]. Caltrans SDC provides a procedure that can evaluate whether P-Delta effects can be ignored in design.

II. BACKGROUND AND LITERATURE REVIEW

P-Delta effects can have a detrimental impact on the seismic response of bridges because of a reduction in both the shear capacity and initial stiffness of RC bridge columns [8], [9], [10]. The reduction in the initial stiffness imposes an increase in the system's natural period and a likely surge in the design displacement demand. However, studies by Jennings and Husid [11] have shown that depending on the profile of an earthquake response spectrum, and the reverse may occur when analyzing or testing slender RC bridge columns under the effect of ground motions. The lateral displacement due to the P-Delta effects needs to be properly addressed in the design as it is against the structure's stability and may cause collapse. The complexity of this problem increases as the structure gets into inelastic deformation. Although it is allowed to neglect the P-Delta effect [12], it is necessary to fully capture the P-Delta effects for a high nonlinearity level and near collapse circumstances. The Caltrans Seismic Design Criteria (SDC) [15] provides the minimum requirements for ordinary bridges' seismic design. These requirements ensure that the bridge will meet the performance goals of the design. Caltrans SDC defines a conservative limit for lateral displacements due to axial load to prevent the P-Delta effects from triggering any stability problems. This goal is met by limiting the ductility demands on structural components. Caltrans SDC states that P-Delta effects shall be neglected [15] if Eq (1) is satisfied, and structural components can be designed based on predefined ductility demands.

$$P\,\Delta_r = 0.2\,M_p \qquad (1)$$

ΔR is the lateral offset between the point of contra-flexure and the plastic hinge base. M_p is the idealized plastic moment capacity of a column calculated by M-φ analysis. In cases in which Eq (1) is not satisfied, it must perform a nonlinear time history analysis to study the P-Delta effects on the column.

III. METHOD

This research is intended to study the reliability of reaching desirable damage levels for columns that comply with the Caltrans SDC criterion to neglect the negative impacts of the P-Delta effects. Structural nonlinear behavior is load path-dependent. Deformation demands depend on ground motion characteristics that vary significantly from one earthquake to another, known as aleatory uncertainty sources. To study the Caltrans SDC method's reliability and the impacts of aleatory uncertainties, nonlinear time history analysis has been incorporated. 26 columns that all comply with the Caltrans SDC criterion for neglecting the P-Delta effects have been subjected to a Far-field earthquake recordset consisting of 44 different earthquake records with similar characteristics, which will be discussed shortly.

A. *General column properties*

Table I shows the material's general properties and the geometry of the columns subjected to this study. The material properties required to define the reinforcing rebar and the concrete are as follows.

TABLE I: Column Material Properties

Concrete Strength, f'c (MPa, ksi)	37 (5.38)
yield Strength, fy (MPa, ksi)	413 (60.0)
Modulus of elasticity, Es (MPa, ksi)	2×105(29,00)
Longitudinal reinforcing steel: yield strain, εy	0.0015
Column diameter, L (m, ft)	1.21 (4)
Cover concrete (cm, in)	5 (2)

B. *Finite element model*

Throughout this research, nonlinear static (pushover) and dynamic analyses were performed using the OpenSees structural analysis platform [16]. OpenSees has been successfully used by other researchers in investigating the nonlinear load-deformation response of RC bridge columns. A circular cross-section is used in this research. The circular cross-section was represented by a fiber-based model originally developed by Taucer et al. [17]and has been implemented in OpenSees by Scott and Fenves [19]. The cross-section shown in Fig.1was subdivided into fibers and assigned uniaxial stress-strain laws available in OpenSees to describe the cover and core concrete's response.

C. *Pushover analysis*

OpenSees[16]structural analysis platform is incorporated to perform nonlinear static analysis (Pushover) and obtain the moment-curvature and load-deformation curves.

Pushover analysis (Fig.1) provides the lateral load and displacement of the structure at different stages, from elastic behavior to the ultimate capacity. In Fig.1 bilinear load-displacement curve is created using the yielding and ultimate capacity of the column. Displacement and load at design target ductility are obtained by linear interpolation between the yielding and the ultimate point.

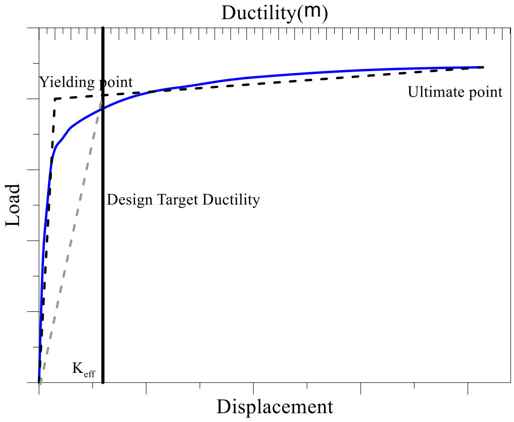

Fig 1: Load-Deformation

D. *Ground motion selection*

Throughout this research, ATC Far-Field, a ground motion recordset, is used. The ground motion set is collected from the Pacific Earthquake Engineering Research Centre (PEER-NGA) database. Table II and Table III tabulate the characteristics of the ground motion set. Following characteristics are common among all these ground motion records.

TABLE II: Ground Motion Properties

Distance R	R > 10 km
Large Magnitude Events	M > 6.5
Equal Weighting of Events	≤ 2 records per event
Strong Ground Shaking	PGA > 0.2g PGV > 15 cm/sec
Source Type	Both Strike-Slip and Thrust Fault Sources
Site Conditions	Rock or Stiff Soil Sites Vs > 180 m/s
Record Quality	Lowest Useable Frequency < 0.25 Hz

Far-Field earthquake record set specifications are tabulated in Table III.

TABLE III: **Ground Motions Records**

EQ ID	Name	PGA (g)	EQ ID	Name	PGA (g)
12011	Northridge	0.52	12092	Landers	0.42
12012	Northridge	0.48	12101	Loma Prieta	0.53
12041	Duzce, Turkey	0.82	12102	Loma Prieta	0.56
12052	Hector Mine	0.34	12111	Manjil, Iran	0.51
12061	Imperial Valley	0.35	12121	Superstition Hills	0.36
12062	Imperial Valley	0.38	12122	Superstition Hills	0.45
12071	Kobe, Japan	0.51	12132	Cape Mendocino	0.55
12072	Kobe, Japan	0.24	12141	Chi-Chi, Taiwan	0.44
12081	Kocaeli, Turkey	0.36	12142	Chi-Chi, Taiwan	0.51
12082	Kocaeli, Turkey	0.22	12151	San Fernando	0.21
12091	Landers	0.24	12171	Friuli, Italy	0.35

E. *Scaling the earthquake records to the target ductility*

Earthquake records were amplified such that the columns reach the target ductility of four with neglecting the P-Delta effects

F. *Perform nonlinear time history analysis*

The model developed in OpenSees is used to investigate the nonlinear load-deformation response of RC bridge columns. The circular cross-section was represented by a fiber-based model, and the concrete cover and core sections were modeled with the "Concrete07" uniaxial concrete material class. The procedure to perform nonlinear time history analysis is as follows.

1) Apply the scaled earthquake record and obtain the load-deformation data (without P-Delta).

2) Compute the maximum displacement and corresponding ductility level.

3) Apply the scaled earthquake record and obtain the load-deformation data (with P-Delta).

4) Compute the maximum displacement and corresponding ductility level.

5) Repeat step 1 to step 4 for all earthquake records.

6) Compare the maximum ductility from the analyses with the Target ductility.

IV. RESULTS

A. *Controlling the Caltrans SDC criterion for neglecting the P-Delta effects*

Caltrans SDC criterion for neglecting the P-Delta effects requires performing pushover analysis. Suppose the ratio of the P-Delta induced moment at the target ductility to the idealized plastic moment is below twenty percent. In that case, the P-Delta effects are negligible, and structural components shall be designed based on provided displacement ductility demands. Table IV presents the results obtained from the pushover analysis and checks the Caltrans SDC criteria for ignoring the P-Delta effects. All columns comply with the Caltrans SDC criterion for neglecting the P-Delta effects. Fig.2 shows moment-curvature and load-displacement curves obtained from pushover analysis for the column with Col-ID 26. In this analysis, the P-Delta effects are neglected.

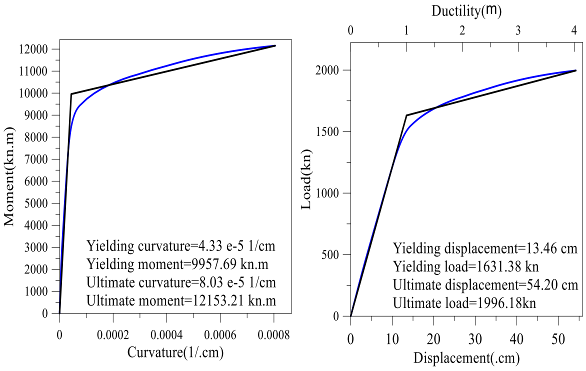

Fig 2: Moment-Curvature and Load-Displacement (Col ID=26)

Table IV is populated by performing a pushover analysis. The first three columns are the axial loads, column heights, and reinforcement ratios of RC bridge columns subjected to this study.

TABLE IV: **Columns Studied in This Research**

Col.ID	Axial.load (Kn)	Height (m.)	ρ_L (%)	M_y (kn.m)	P-D moment (kn.m)	$\frac{P\text{-}D}{M_y}$
1	1730	4.88	1	2966	337.49	0.11
2	1730	6.10	1	2966	385.28	0.13
3	1730	7.32	1	2966	441.77	0.15
4	1730	8.53	1	2966	521.31	0.18
5	1730	4.88	2	5160	520.86	0.10
6	1730	6.10	2	5160	575.09	0.11
7	1730	7.32	2	5160	652.26	0.13
8	1730	8.53	2	5160	758.58	0.15
9	1730	9.75	2	5160	888.51	0.17
10	1730	10.97	2	5160	1035.39	0.20
11	2620	4.88	1	3213	535.55	0.17
12	2620	6.10	1	3213	598.14	0.19
13	2620	4.88	2	5355	801.97	0.15
14	2620	6.10	2	5355	881.39	0.16
15	2620	7.32	2	5355	1002.85	0.19
16	2620	4.88	3	7301	1014.04	0.14
17	2620	6.10	3	7301	1100.70	0.15
18	2620	7.32	3	7301	1248.60	0.17
19	2620	4.88	4	9272	1237.52	0.13
20	2620	6.10	4	9272	1333.56	0.14
21	2620	7.32	4	9272	1494.34	0.16
22	2620	8.53	4	9272	1707.65	0.18
23	3460	4.88	2	5611	1087.70	0.19
24	3460	4.88	3	7471	1376.61	0.18
25	3460	4.88	4	9422	1668.67	0.18
26	3460	6.10	4	9422	1795.67	0.19

B. *Scaling the earthquake records*

The earthquake records were amplified to study the reliability of reaching desirable levels of damage using an iterative algorithm. The columns reach to target ductility of four without neglecting the P-Delta effects. Fig.3 shows the scaled earthquake record (EQ ID=120111) for a column (Col-ID=26).

C. *Performing nonlinear time –history analysis*

The scaled earthquake records are applied to the RC bridge columns. This analysis is performed with and without the inclusion of the P-Delta effects. The desirable response is defined as if P-Delta effects have a negligible impact on the maximum ductility. Fig. 4 shows the nonlinear time history analysis with the inclusion of the P-Delta effects for a Column (Col-ID=26) as the scaled earthquake record is applied to it (EQID=120111).

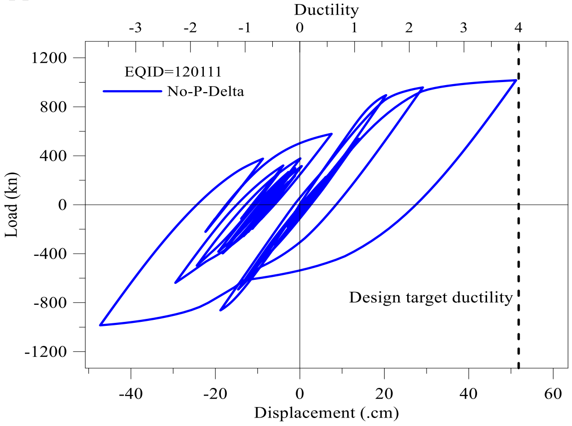

Fig 3: Scaling the Earthquake Record to Target Ductility (Col ID=26)

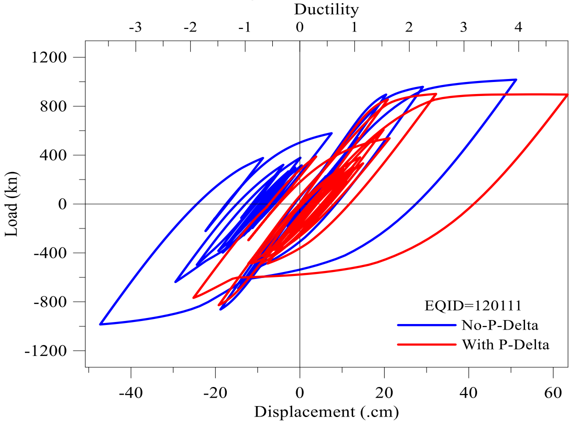

Fig 4: Nonlinear Time History Analysis (Col ID=26)

The same analysis is performed for the entire earthquake records defined in the method section, and the maximum ductility with and without P-Delta was collected. Fig.5 shows the obtained Displacement ductility for the column with Col ID=26 for all earthquake records.

D. *Distribution of displacement ductility*

Fig.6 presents the histogram for the maximum ductility with P-Delta effects. Lognormal distribution with parameters of (μ=1.43, σ=0.08) best fitted the results.

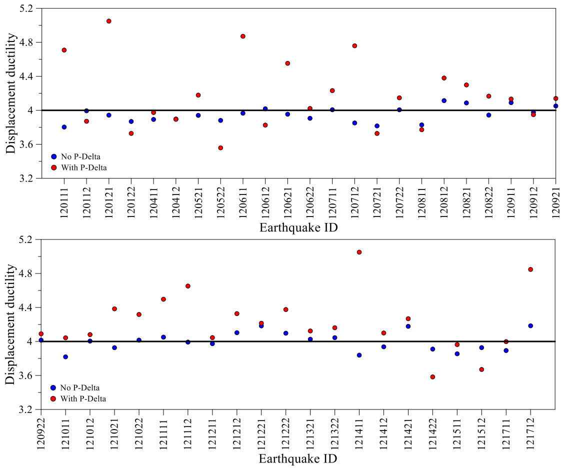

Fig 5: Maximum Ductility for All Earthquake Records(Col ID=26)

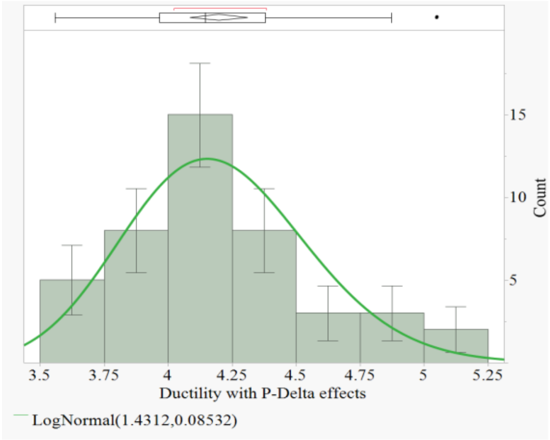

Fig 6: Histogram Plot

Quantiles of the observed data are presented in Table V and can be used to find the desired response probability. For instance, there is a twenty-five percent probability that this column reaches ductility 3.96 or less with the inclusion of the P-Delta effects.

TABLE V: Summary of Statistical Analysis (Col ID=26)

Quantiles		Summary Statistics	
100%(max)	5.05	Mean	4.19
99.5%	5.05	Std Dev	0.36
97.5%	5.05	Std Err Mean	0.05
90%	4.80	Upper 95% Mean	4.31
75%(quartile)	4.37	lower 95% Mean	4.08
50%(median)	4.14	N	44
25%(quartile)	3.96		
10%	3.72		
2.5%	3.56		
0.5%	3.55		
0%(min)	3.55		

Table VI presents the results of hypothesis testing on the mean using the t-test. Hypothesized value for the mean was four, which is recommended design target ductility by the Caltrans SDC for single column bents supported on a fixed foundation. The p-value for the two-sided and one-sided tests are provided in Table VI. The null and alternative hypotheses for one-sided testing are as follows.

H_0: $\mu=4$ The average maximum ductility is 4

H_a: $\mu>4$ The average maximum ductility is above 4

At the a= 0.05 level, since p = 0.0004< 0.05, the null hypothesis is rejected. The alternative hypothesis is accepted, which means we have evidence to show that the average maximum ductility with the P-Delta effects' inclusion is above 4.

TABLE VI: Test Mean Results (Col ID=26)

Test mean	
Hypothesized value	4
Actual estimator	4.19
DF	43
Std Dev	0.36
t-Test	
Test statistics	3.58
Prob>|t|	<0009*
Prob>t	<0004*
Prob<t	0.9996

E. 95 % confidence interval for average ductility

The nonlinear time-history analysis is performed on all columns and a 95% confidence interval with calculated mean and standard deviation.

Table VII presents the mean, standard deviation, and the 95 % confidence interval for all columns. Comparing the mean of the maximum ductility with the target ductility of four indicates a significant difference between the structural responses of these columns with the inclusion of the P-Delta effects.

TABLE VII: Columns Studied in This Research

Col.ID	N	Mean	STD	lower 95% CI	Upper 95% CI
1	44	4.43	0.87	4.17	4.69
2	44	4.72	1.43	4.30	5.14
3	44	4.64	0.90	4.37	4.91
4	44	4.66	0.76	4.44	4.88
5	44	4.26	0.28	4.18	4.34
6	44	4.58	1.30	4.20	4.96
7	44	4.40	0.56	4.23	4.57
8	44	4.30	0.39	4.18	4.42
9	44	4.55	0.67	4.35	4.75
10	42	4.70	1.34	4.29	5.11
11	44	4.34	0.56	4.17	4.51
12	44	4.32	0.61	4.14	4.50
13	44	4.34	0.55	4.18	4.50
14	44	4.36	0.49	4.22	4.50
15	43	4.35	0.49	4.20	4.50
16	44	4.33	0.52	4.18	4.48
17	44	4.36	0.39	4.24	4.48
18	44	4.39	0.55	4.23	4.55
19	44	4.28	0.47	4.14	4.42
20	44	4.32	0.38	4.21	4.43
21	43	4.33	0.45	4.20	4.46
22	44	4.18	0.26	4.10	4.26
23	44	4.16	0.43	4.03	4.29
24	44	4.15	0.37	4.04	4.26
25	44	4.18	0.34	4.08	4.28
26	44	4.20	0.37	4.09	4.31

Fig.7 shows the 95 % confidence interval and the mean of the maximum ductility for all columns subjected to this study.

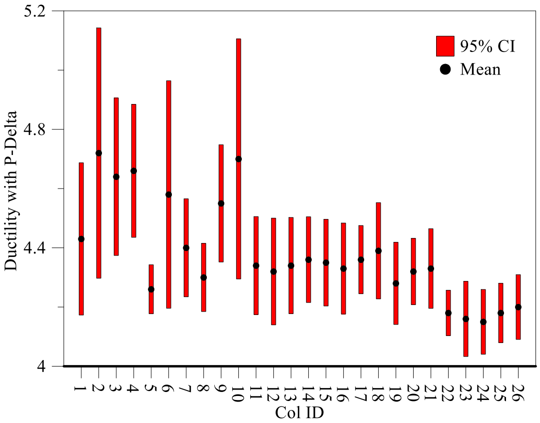

Fig 7: Magnetization as a Function of Applied Field

The upper 95 % confidence interval for columns shows that although these columns go beyond the target ductility of four with the inclusion of the P-Delta effects, the excessive P-Delta induced moment is not adequate to cause major stability problems such as collapse.

V. CONCLUSIONS

Caltrans SDC controls the P-Delta effects using a conservative limit for lateral displacements due to axial load. The ductility demand limit proposed by the Caltrans SDC for single bent columns supported on a fixed foundation was subjected to study in this research. Twenty-six columns complying with the Caltrans SDC criterion for neglecting the P-Delta effects were subjected to the Far-Field earthquake recordset, and their maximum displacement ductility was calculated. The Caltrans SDC above design target ductility recommended the average maximum ductility for all columns. The difference in maximum obtained ductility with the inclusion of P-Delta effects was significant, but it wasn't strong enough to cause a collapse

Caltrans SDC uses pushover analysis in defining its criterion for neglecting the P-Delta effects, which disregards the fact that as columns experience yielding and unloading under dynamic loading, their properties change (load path dependence). Thus this method's application should be exercised with extra caution.

For future work, this research can be extended by looking at columns that fail to satisfy the Caltrans SDC criterion to neglect the P-Delta effects and compare the obtained results with the results of this research to study the possibility of finding pathways to improve the Caltrans SDC procedure for consideration of the P-Delta effects.

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