A BNWF APPROACH TO ASSESS THE RESPONSE OF SINGLE PILE SUBJECTED TO FAR-FIELD AND NEAR-FIELD EARTHQUAKES

B. E. Ajom, K. Dasgupta & A. Dey

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Presented by

Dr Arindam Dey

Associate Professor

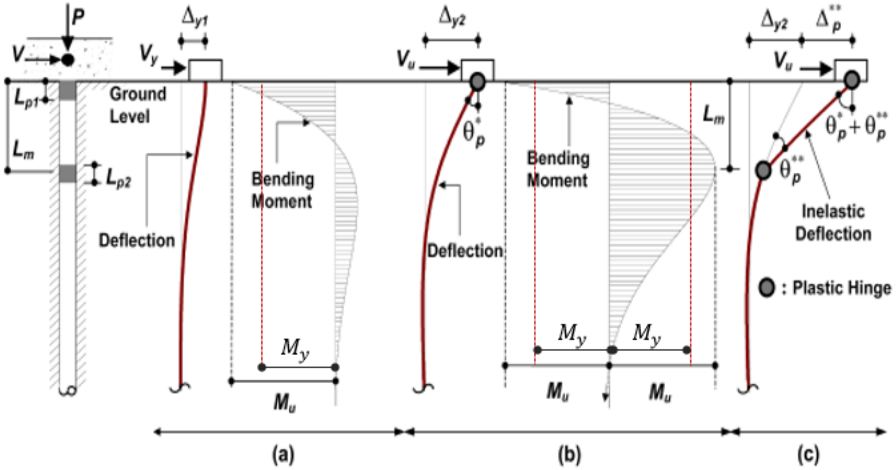
Department of Civil Engineering
Indian Institute of Technology Guwahati, India

Outline of the presentation

- Behaviour of single fixed-head piles
- Recommendations for plastic hinge length by Indian codes of practice
- Ground motion selection
- Pile-soil interaction modelling using BNWF approach
- Validation study
- Parametric investigation
- Results
- Conclusion

Behaviour of single fixed-head piles

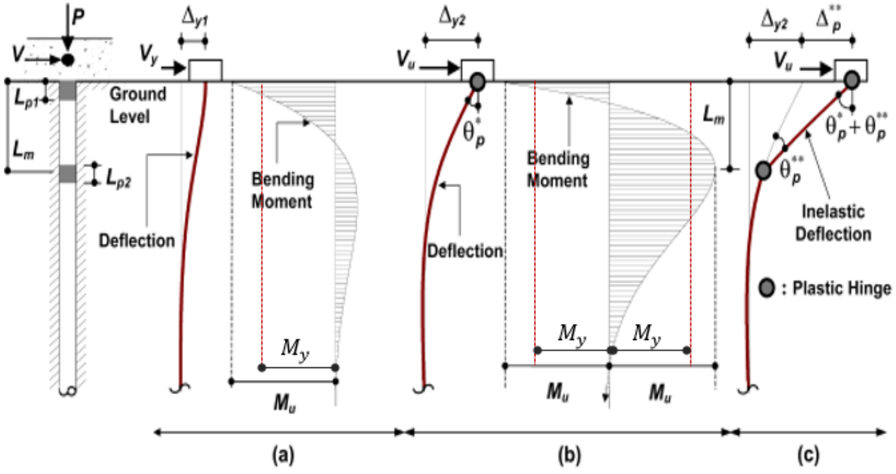
- The key mechanism to attain ductile performance solely involves the development of flexural plastic hinges along the pile length
- The first yield limit state of the pile is characterised by the maximum Bending Moment (BM) developed at any location along the length of the pile where yield moment (M_y) of the pile is reached
  - A flexural plastic hinge is assumed to develop at that location
- Figure (a) shows the formation of the flexural plastic hinge at the top of the pile with the centre of rotation occurring at the ground level



(Song et al., 2005)

Behaviour of single fixed-head piles

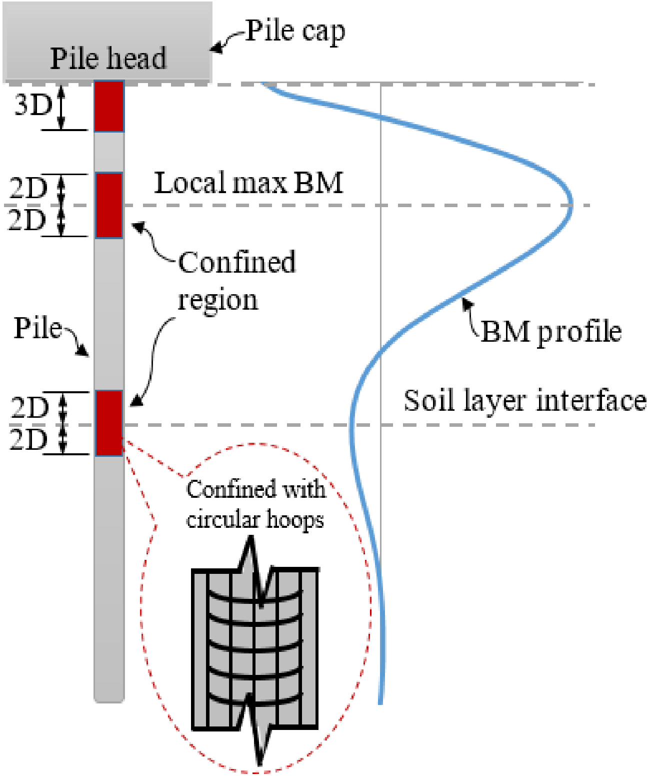
- With increasing displacement:
  - Redistribution of internal forces occurs
  - Leading to an increase in BM in the non-yielding portion of the pile
  - Resulting in the formation of a second flexural plastic hinge at a depth L_m (Fig. b)
- L_{p1} and L_{p2} are the first and second plastic hinge lengths, respectively
- After formation of the second plastic hinge, further displacement induces large inelastic rotations at both hinges until the pile reaches the ultimate limit state (Fig. c).
- Several studies have been conducted to estimate the Plastic Hinge Length (PHL) of piles (Budek et al., 2000; Chai, 2002; Heidari and Naggar, 2018)



(Song et al., 2005)

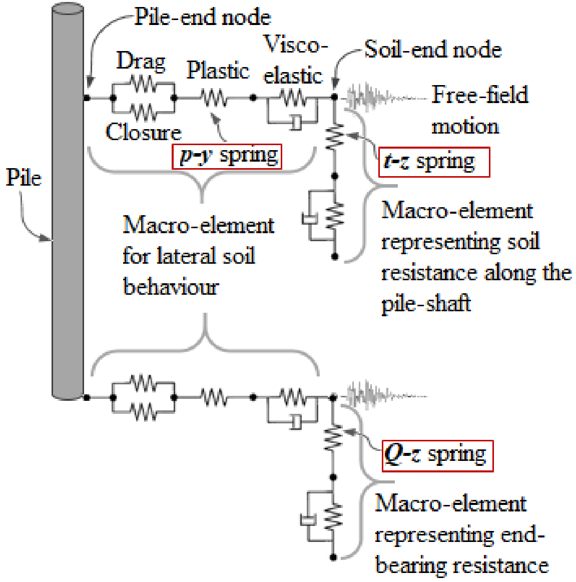
Recommendations for PHL by Indian codes of practice

- IRC:112-2020 recommends certain critical locations of potential plastic hinges
  a. At pile head (flexural plastic hinge)
  b. At location with a local maximum BM well below the ground surface (flexural plastic hinge)
  c. At interface of soil layers (shear plastic hinge)
- At those locations, confining reinforcement should be provided along the specified vertical length of the pile
  - At location type (a), 3D (D = pile diameter)
  - At location type (b), 2D at each side of the point of maximum moment
  - At location type (c), 2D at each side of the soil layer interface



Pile-soil interaction modelling using Beam on Nonlinear Winkler Foundation (BNWF) approach

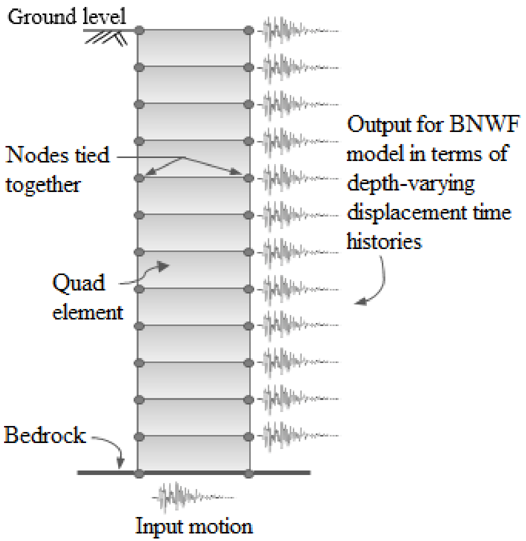
- For the lateral soil-pile interaction, the Nonlinear (NL) behaviour is characterized as consisting of visco-elastic, plastic and gap components in series
- These soil springs are generated using zero-length elements each consisting of two nodes sharing the same location
- $p-y$, $t-z$ and $Q-z$ curves are used to simulate the plastic components of the macro elements along lateral and axial directions
    - Hysteretic damping arising from the material nonlinearity is considered
- The pile is discretized into 0.5 m long displacement beam-column elements
- The NL springs are attached to each pile node at one end and are applied with DTHs at the other for conducting dynamic analyses

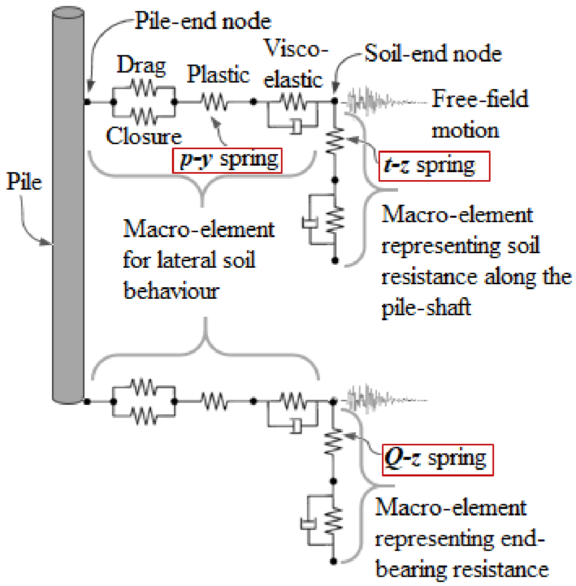


Pile-soil interaction modelling using BNWF approach

Two-step process

1. NL site response analysis to determine the free-field motions within the soil deposit
2. Pile-soil interaction using a BNWF model
   - Pile connected to a series of NL soil springs
   - Free-field Displacement Time Histories (DTHs) at each depth are applied to the free ends of the lateral springs



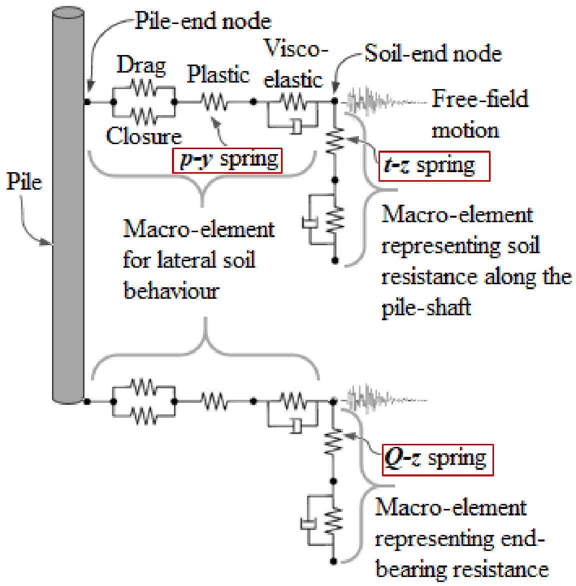


Pile-soil interaction modelling using BNWF approach

- The lateral soil resistance-deflection ($p - y$) NL relationship for sand at any specific depth H,

$$p = A \times p_u \times \tan h\left[\frac{k \times H}{A \times p_u} \times y\right] \qquad \text{(API 2000)}$$

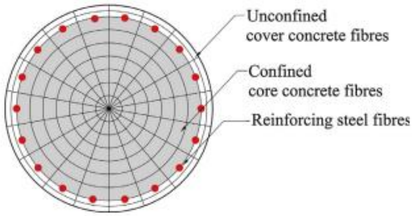
A = factor accounting for cyclic or static loading condition
= 0.9 for cyclic loading
= $\left(3.0 - 0.8\frac{H}{D}\right) \geq 0.9$ for static loading
D = average pile diameter from surface to depth (in m)
p_u= ultimate bearing capacity at depth H (in kN/m)
k = initial modulus of subgrade reaction (in kN/m^3)
y = lateral deflection (in m)

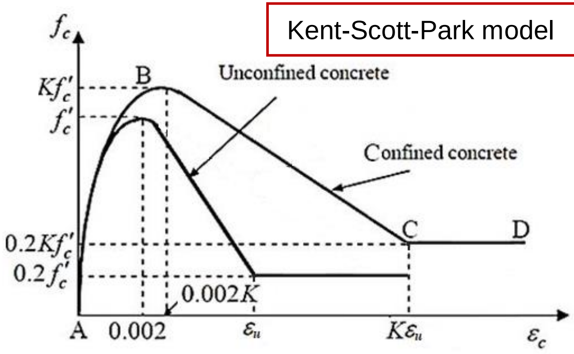


Fibre model of the pile section

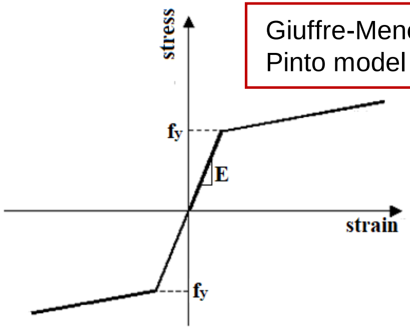
- The fibre-based technique is adopted to model the NL response of the reinforced concrete (RC) piles.
- The cross-section of the RC member is divided into a number of small segments called fibres.
- The fibres are assigned with constitutive material models to represent cover concrete, core concrete and longitudinal steel reinforcement in the RC section
    - For steel, Giuffre-Menegotto-Pinto model
    - For cover and core concrete, Kent-Scott-Park model
- To enhance the strength and ductility of core concrete due to the confinement effects, a factor K has been multiplied to the peak strength and the corresponding strain of the concrete where $K = 1.25\left(1 + \frac{\rho_s f_{yh}}{f_c'}\right)$

  where, ρ_s and f_{yh} are volume ratio and yield strength of transverse reinforcement, respectively and f_c' is the cylinder strength of concrete





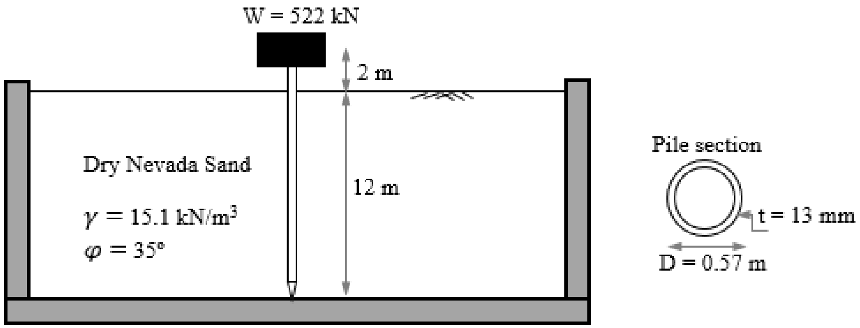
Kent-Scott-Park model

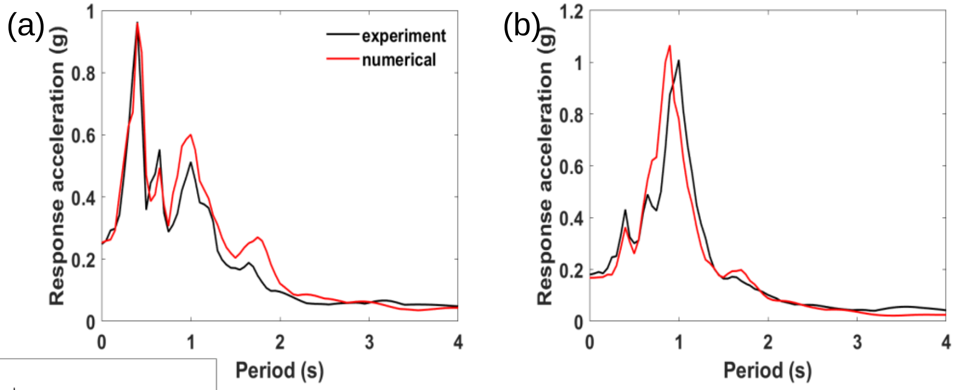


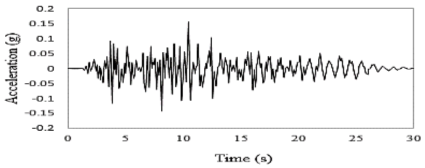
Giuffre-Menegotto-Pinto model

Validation study

- Centrifuge test (No. 12) conducted by Gohl (1991)
- Steel pipe pile in a homogeneous sandy soil profile
- A horizontal acceleration record with a peak acceleration of 0.15 g is given as the input at the base of the system
- Acceleration response spectra comparing the measured responses of (a) free-field motion at ground surface and (b) pile-head motion, from the centrifuge test with the numerical results
    - Agreeable match







Parametric investigation

Design of piles
- IS:2911.1.2-2010
- IS:456-2000
- SP:16-1980
- IRC:112-2020

Pile details
- An RC circular single pile
- Bored cast in-situ
- 25 m long
- Fixed-head, floating pile

Pile diameters
- 0.7 m
- 1.2 m

Soil type
- Loose sand φ = 29 °

Longitudinal reinforcement percentages
- 0.4 %
- 1 %
- 2 %
- 4 %

Material grades
- Concrete: M40 (f_{ck} = 40 MPa)
- Longitudinal reinforcement: Fe500
- Transverse reinforcement: Fe250

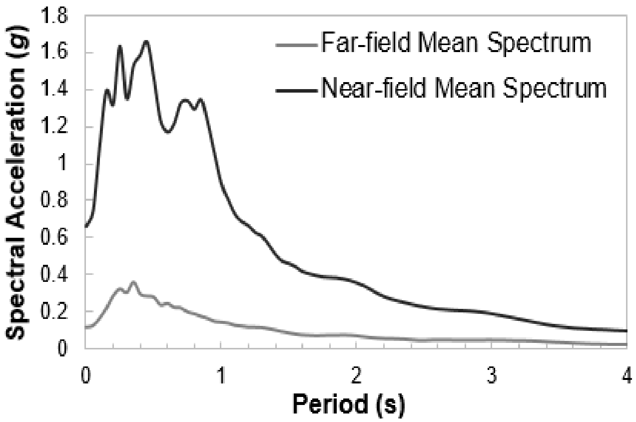
Ground motion selection

- Five far-field (FF) and four near-field (NF) ground motions (GMs)
- Peak Horizontal Accelerations (PHAs) ranging from 0.036 to 0.854.

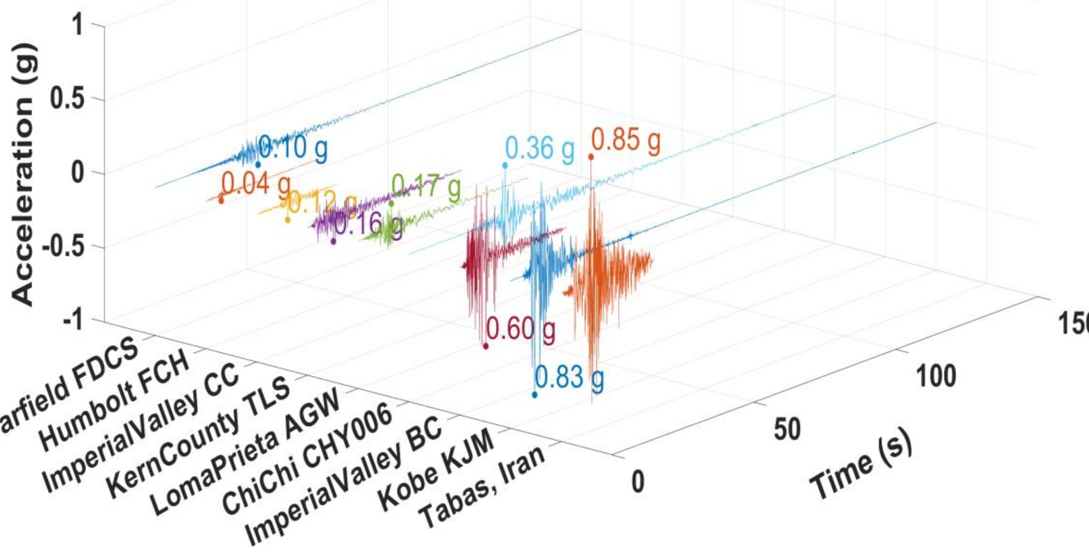
	No.	Earthquakes	Year	Station	Dist. (km)	Comp.	*M*	PHA (*g*)	PHV (cm/s)	Peak Disp. (cm)
Far-field motions	1	Darfield	2010	FDCS	91.59	NW	7.0	0.102	13.31	3.74
	2	Humbolt Bay	1937	Ferndale City Hall	71.57	225	5.8	0.036	2.36	0.35
	3	Imperial Valley	1979	Coachella Canal	50.1	045	6.53	0.116	12.83	2.58
	4	Kern County	1952	Taft Lincoln School	38.89	021	7.63	0.159	15.22	6.10
	5	Loma Prieta	1989	Agnews State Hosp.	24.57	000	6.93	0.169	33.50	23.88
Near-field motions	6	Chi-Chi	1999	CHY006	9.76	N	7.62	0.358	42.32	17.00
	7	Imperial Valley	1979	Bonds Corner	2.66	140	6.53	0.598	46.73	20.21
	8	Kobe	1995	KJMA	0.96	000	6.9	0.834	91.07	21.10
	9	Tabas, Iran	1978	Tabas	2.05	Longi.	7.35	0.854	98.81	37.52

Ground motion selection

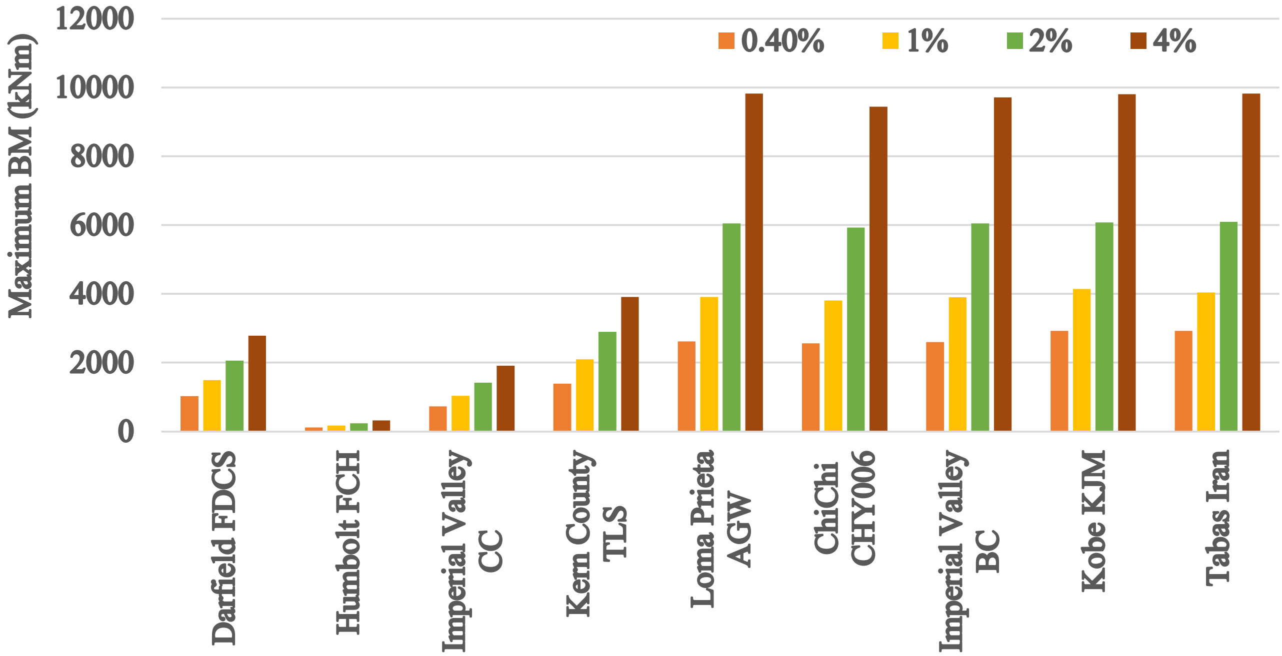
- The mean spectral response of the near-field GMs is significantly greater than that of their far-field counterparts



Baker (2007) suggested that earthquakes with an original ground motion peak velocity exceeding 30 cm/sec are considered as near-field earthquakes.



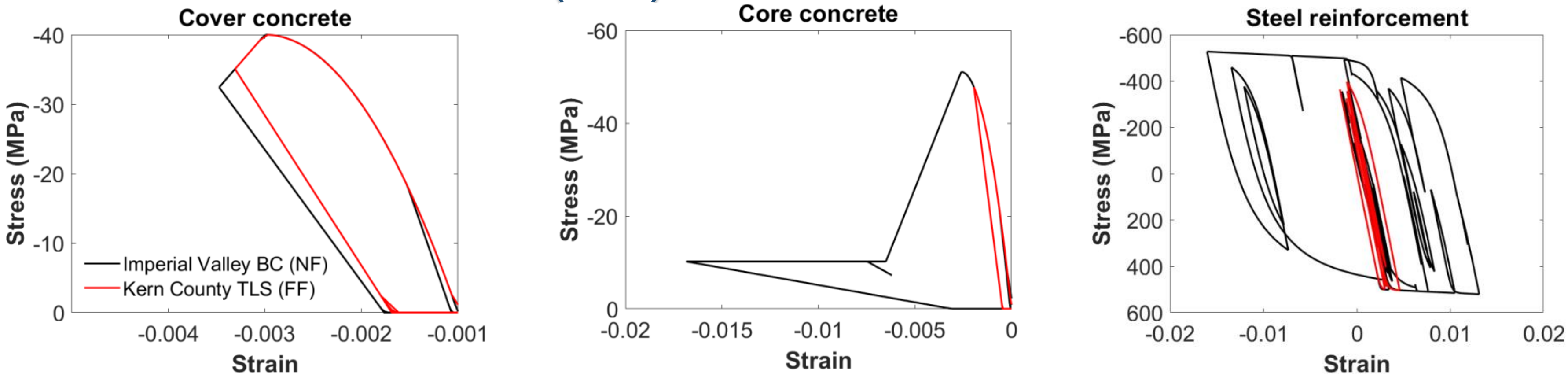
Results: Influence of ground motion characteristics



- Large BMs have been observed under all the NF earthquakes and the Loma Prieta earthquake (FF)
- Observed for all the considered reinforcement percentages

Results: Material stress-strain (axial) behaviour

Negative = compression, Positive = tension

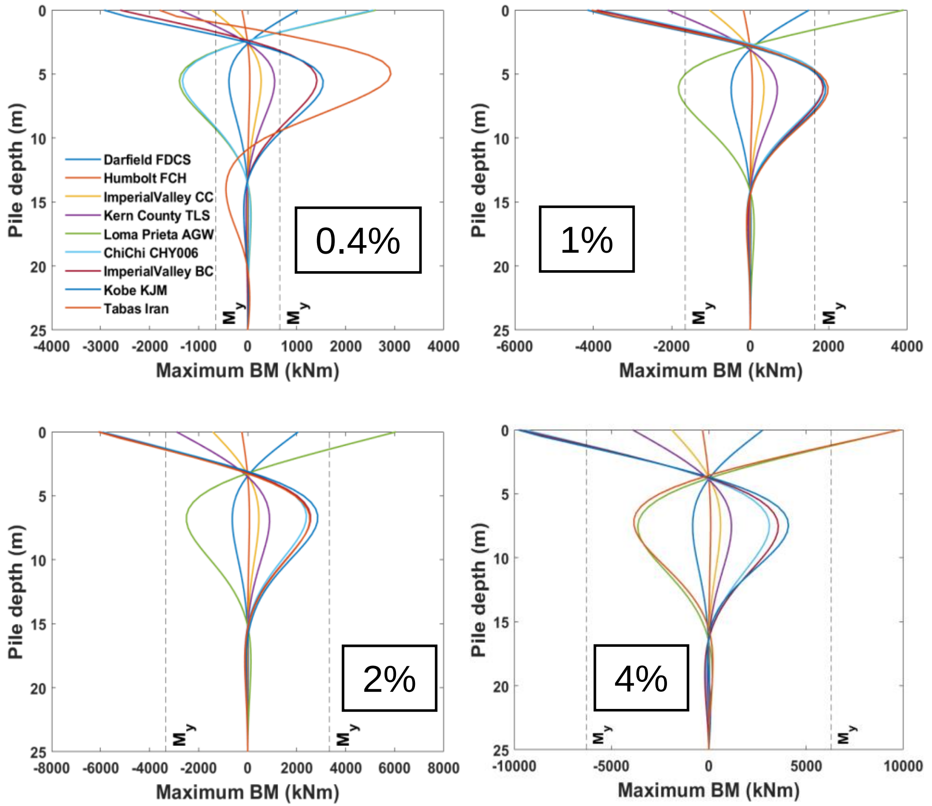


Maximum stress-strain curves for the 1.2 m diameter pile with 0.4% longitudinal reinforcement under a NF and a FF earthquake

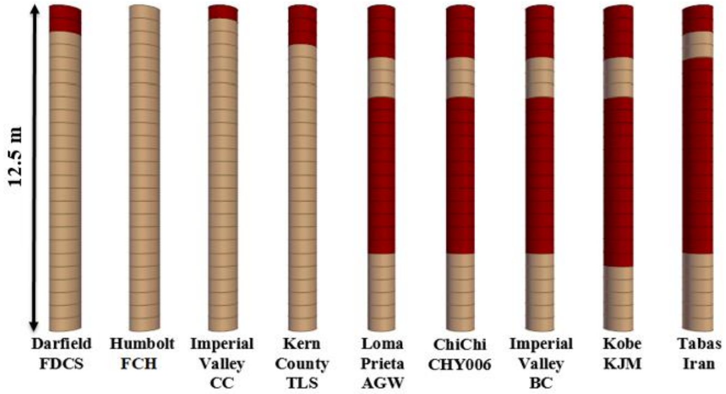
- Cover concrete reaches peak strength in both cases but undergoes more strain in case of NF earthquake compared to the FF one
- Core concrete achieves ultimate strength under NF earthquake, also undergoes higher strain, contrasting with FF earthquakes where it fails to reach peak strength
- Reinforcing steel undergoes greater strain during the NF earthquake in contrast to the FF one
- The differences in stress-strain response among these materials indicate varying levels of stress and strain intensity based on the proximity of the earthquake.

Results: Plastic hinge zone

- Yield moments, M_y for 1.2 m diameter pile:
    - 655 kNm, 1653 kNm, 3331 kNm and 6308 kNm for 0.4 %, 1 %, 2 % and 4 % longitudinal reinforcement percentages, respectively
- For 0.4% and 1% longitudinal reinforcement, plastic hinges are observed at two distinct zones: near the pile-head, where maximum BM occurs, and at a location with a local maximum BM in the reverse direction
- This trend is consistent for all NF earthquakes and for the Loma Prieta earthquake among the FF earthquakes.

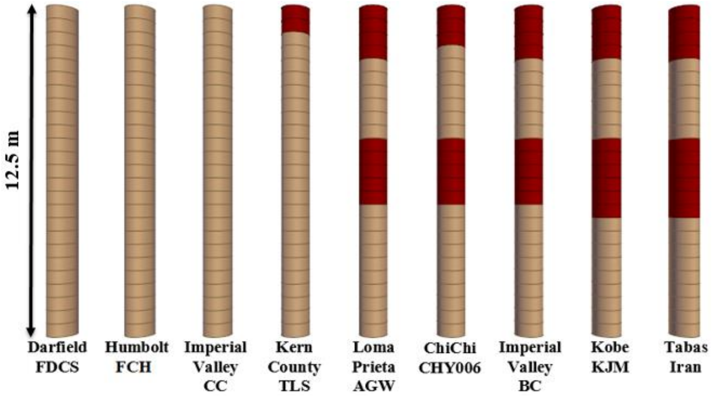


Results: Plastic hinge zone

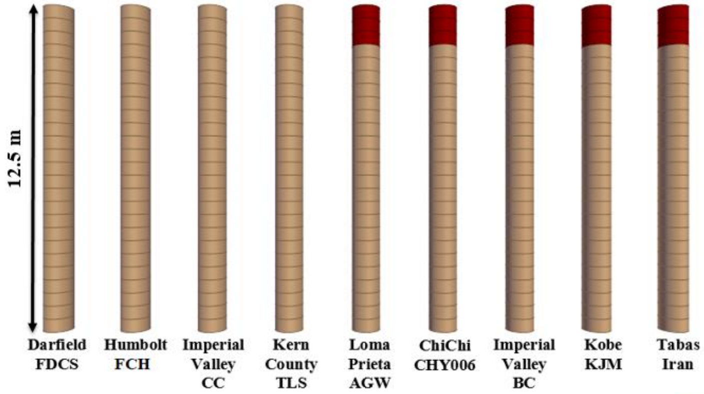


0.4%

1%



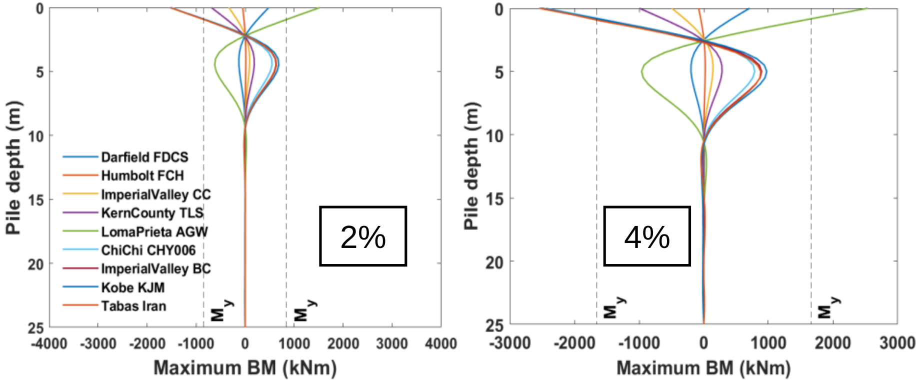
2% and 4%

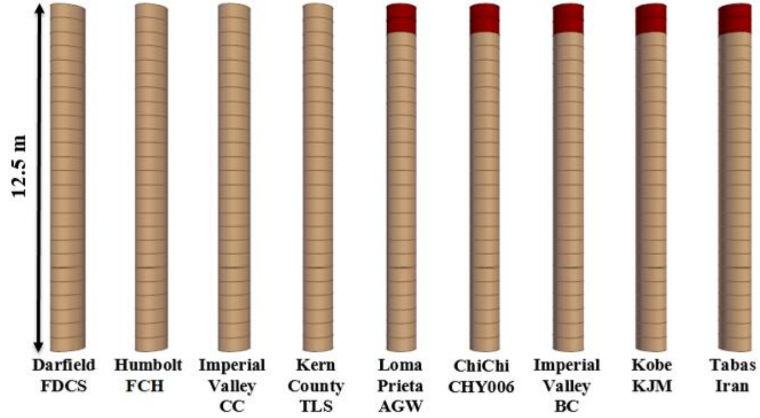


- For other FF earthquakes with lesser peak ground displacements (PGDs), plastic hinges are observed only near the pile-head
- For 2% and 4% longitudinal reinforcement, plastic hinges are observed to form only near the pile-head under NF and Loma Prieta earthquakes.

Results: Plastic hinge zone

- Yield moments, M_y for 0.7 m diameter pile:
  - 848 kNm and 1657 kNm for 2 % and 4 % longitudinal reinforcement percentages, respectively
- Plastic hinges formed only at the pile head for earthquakes having higher PGD





2% and 4%

Results: Plastic hinge length

- The IRC-recommended values for L_{p1} are conservatively aligned with the observed L_{p1} values for both the 1.2 m and 0.7 m diameter piles
- For 0.4 % reinforcement, the observed values of L_{p2} exceed the prescribed plastic hinge length for the 1.2 m diameter pile
    - For higher reinforcement percentages, observed L_{p2} values are well within the prescribed limit for both diameter piles
- Higher reinforcement percentages can mitigate plastic hinging at large depths within the piles

	1.2 m dia. pile						0.7 m dia. pile	
Prescribed PHL as per IRC:112-2020	L_{p1} = 3.6 m, L_{p2} = 4.8 m						L_{p1} = 2.1 m, L_{p2} = 2.8 m	
Earthquakes	0.4 %		1 %		2 % and 4 %		2 % and 4 %	
	Observed L_{p1} (m)	Observed L_{p2} (m)	Observed L_{p1} (m)	Observed L_{p2} (m)	Observed L_{p1} (m)	Observed L_{p2} (m)	Observed L_{p1} (m)	Observed L_{p2} (m)
Darfield FDCS	1	-	-	-	-	-	-	-
Humbolt FCH	-	-	-	-	-	-	-	-
Imperial Valley CC	0.5	-	-	-	-	-	-	-
Kern County TLS	1.5	-	-	-	-	-	-	-
Loma Prieta AGW	2	6	2	2.5	1.5	-	1	-
Chi Chi CHY006	2	6	1.5	2.5	1.5	-	1	-
Imperial Valley BC	2	6	2	2.5	1.5	-	1	-
Kobe KJM	2	6.5	2	3	1.5	-	1	-
Tabas, Iran	1	7.5	2	3	1.5	-	1	-

Conclusion

- The pile response under the Loma Prieta earthquake is similar to that of the near-field earthquakes.
    - This similarity occurs despite the Loma Prieta earthquake having a lower PHA and being classified as far-field based on the epicentral distance.
    - This indicates that classifying ground motions solely by epicentral distance may be insufficient.
- It is always advisable to avoid plastic hinging deep below the ground surface where retrofitting at such a great depth is not feasible.
    - Providing higher reinforcement percentages can mitigate plastic hinging at large depths within the piles.
- Codal recommendations for plastic hinge lengths in single piles consider only the pile diameter.
    - Longitudinal reinforcement percentages should also be taken into account when prescribing PHL for piles.

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THANK YOU