Development of dissipative controlled rocking system for bridge columns supported on monopiles

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ABSTRACT

In this research, a low-damage seismic design detail is developed for bridge columns supported on monopile foundations. The low-damage system aims to minimise, and potentially eliminate, the repair time and costs to a bridge after an earthquake. The low-damage design uses a dissipative controlled rocking (DCR) connection at the base of the column, which replaces the column plastic hinge. The DCR system combines unbonded post-tensioning and replaceable internal dissipaters to provide self-centring and energy absorption capabilities for the bridge pier, respectively. Additionally, this research validates the lateral seismic response of a DCR bridge pier with the contribution of soil-foundation-structure interaction. This paper includes a description of the prototype structure being investigated, an overview of the proposed experimental testing that will occur as part of the experimental campaign, and the results of the numerical modelling that aims to predict the behaviour of the protype and benchmark structure during testing.

1 INTRODUCTION

Dissipative controlled rocking (DCR) systems are an established engineering technology that has been successfully adopted into building design (Canterbury Earthquake Royal Commission 2012) and experimentally validated for application of bridge columns (Mashal and Palermo 2019; Han et al. 2019). DCR systems, when applied to column joints, combine a self-centring mechanism with dissipation devises to reduce structural damage at plastic hinge zones and residual displacements in columns. The combination of recentring and dissipating components typically results in a "flag-shaped" hysteresis response that passes through the origin, indicating zero residual column displacement.

The development of the DCR connection originates back to the joint United States-Japan research program called PREcast Seismic Structural System (PRESSS), which was coordinated by the University of California, San Diego (Priestley 1991, 1996; Priestley et al. 1999; Stanton et al. 1991, 1997; Stone et al. 1995). Many of the connections tested in the PRESSS program were for building structure applications; one of which is called a hybrid jointed ductile connection and is referred to as a DCR connection in this paper. Research has since been extended for application to bridges (Mander and Cheng 1997; Palermo et al. 2004, 2005, 2007; Wacker et al. 2005; Palermo and Pampanin 2008; Marriott 2009; White and Palermo 2016; Guerrini et al. 2015; Mashal and Palermo 2019); however, all research to-date has assumed a rigid foundation at the base of the column.

Unlike buildings that are often founded on rigid foundations, the lateral seismic response of bridge columns that are supported on a monopile is influenced by the soil-foundation-structure interaction. Neglecting the contribution of foundation rotations in the design of DCR columns underestimates the drift capacity of the pier. The research presented in this paper explores how foundations susceptible to rotations, like piles, affect the performance of a DCR system. Specifically, this research studies how additional rotations in the pile head delay the onset of column rocking. The results of the predictive numerical analysis are presented.

2 PROTOTYPE STRUCTURE

The prototype structure chosen is representative of a typical New Zealand highway bridge (Fig. 1). The bridge consists of two spans that measure 20m in length. The pier is comprised of a single 1.5m diameter circular column on a 1.8m diameter circular pile shaft, and a hammerhead-type capping beam. The bridge deck consists of standard 1525mm deep precast Super-Tee beams with an overall width of 10.5m. The deck, beam type and dimensions are consistent with the standard designs presented in the Transport Agency's publication Standard Precast Concrete Bridge Beams: Research Report 364 (NZ Transport Agency 2008). The prototype is assumed to be of importance level 3, have a 100-year design life, located in Christchurch on non-liquefiable soil, and is not susceptible to near-fault effects.

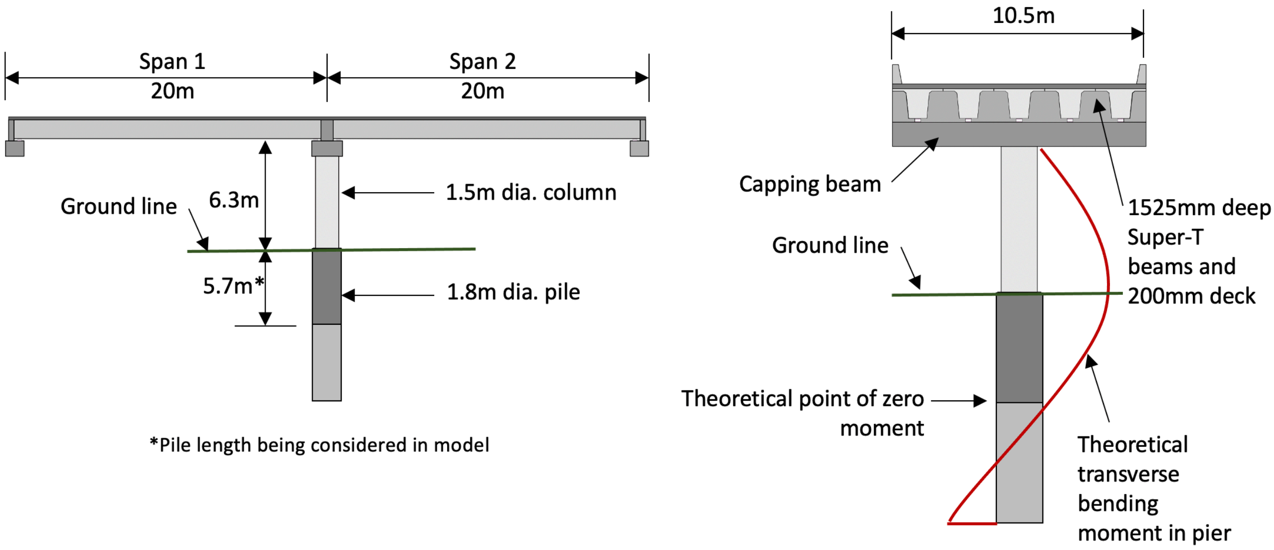


Figure 1: Prototype bridge structure: (left) longitudinal profile and (right) elevation view.

3 SPECIMEN DESIGN

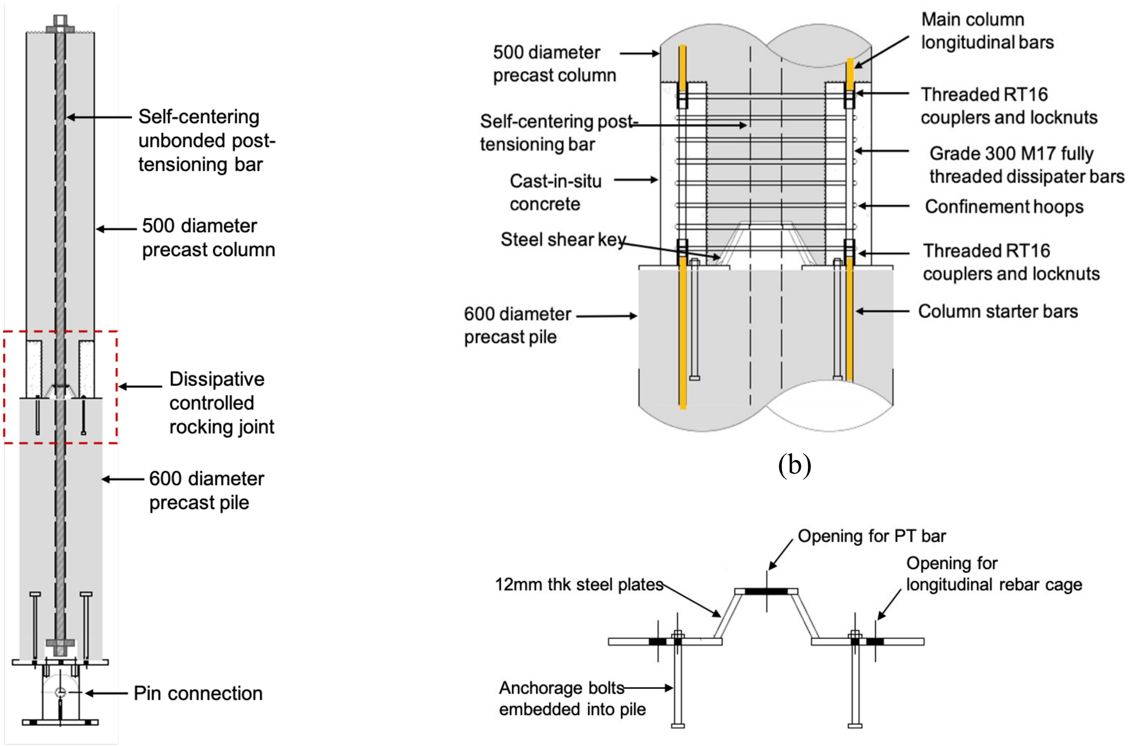
A specimen that is scaled one-third of the protype will be investigated as part of an experimental test programme. The specimen is a post-tensioned single cantilever bridge pier with a replaceable DCR connection type at the base of the column where a plastic hinge is likely to form, like that shown in Figure 2. The detail adopted for the DCR connection utilizes conventional construction materials and forms that are expected to yield a similar cost as a monolithic connection.

The specimen is post-tensioned for self-centring and constructed with replaceable internal dissipaters at the rocking joint. The pier consists of a 500mm diameter precast column with a design height of 2.1m and is supported on a single 600mm diameter precast pile. Since it is uneconomical to construct the pile at its full height, only the upper segment measuring to the theoretical point of zero moment was taken into consideration.

As a result, the pile is 1.9m tall and pinned at the base, which will allow the pile head to experience rotations. The effects of translation do not need to be considered since only relative displacements are of relevance.

The dimensions, design strength, and design displacement of the specimen are scaled from the designed prototype structure aforementioned. NZS3101:2006 (Standards New Zealand 2006) was used to design and detail the reinforcement cage in the column and pile. The PRESSS design handbook (Pampanin et al. 2010) was used to size the required fuse area and fuse length of the dissipaters and determine the size and initial post-tensioning force required for the central post-tensioning bar.

A single 50mm diameter fully threaded post-tensioning bar is used to simulate both the gravity and post-tensioning loads in the pier. The post-tensioning bar is debonded inside a 75mm diameter duct the full length of the column and pile.



(a) (b) (c)

Figure 2: (a) Specimen bridge pier supported on a monopile with a DCR joint at the base of the column. (b) DCR connection detail. (c) Steel shear key.

A steel shear key, shown in Figure 2, is provided at the rocking joint for shear and torsion restraint, as well as protection at the rocking surface. The shear key is fabricated from welded plates to form a rectangle with inclined edges at the centre of the column. An opening is provided at the top of the shear key to allow post-tensioning to pass through. The shear key assembly is welded on a 600mm diameter base plate, which sits on the pile. Bolts that restrain the shear key assembly are cast into the pile, which allows the shear key to be removed and reused. Additional holes were tapped into the shear key's base plate for the longitudinal reinforcement to pass through.

The dissipative devices used in the specimen are Grade 300 fully threaded steel rods. The dissipaters are 16mm in diameter, 380mm in length and are wrapped in debonding grease tape (Denso Tape). The dissipaters are joined to the permanent longitudinal column and pile reinforcement through threaded couplers. The use of fully threaded bars facilitates the installation and replacement of the dissipative bars because the couplers and locknuts can be fully screwed back onto the threaded rods before being screwed to the connecting column and pile longitudinal reinforcement. After the dissipaters are installed, column hoops are distributed into place and fibre reinforced grout is cast at the joint. Refer to Figure 3 for the DCR joint installation sequence.

The internal dissipation solution proposed in this research is a variation to the solution developed by White and Palermo (2016), in which the dissipaters were constructed using Grade 300 steel bars with a reduced section at the centre, and threaded ends to connect to the permanent reinforcement. The fully threaded dissipaters utilised in this research were fabricated by Ancon, who also provided the couplers and locknuts. Fully threaded bars have the advantage of being cut to any length, which reduces fabrication costs and can allow for additional adjustments at the time of installation.

White and Palermo (2016) also utilised steel armouring at the rocking joint to prevent damage to the concrete from rocking. In addition, the column tested by White and Palermo (2016) was supported on a footing with a shallow socket which acted as a shear key. Both the issue of concrete damage at the rocking surface and shear transfer is accounted for in this research by use of a single steel shear key.

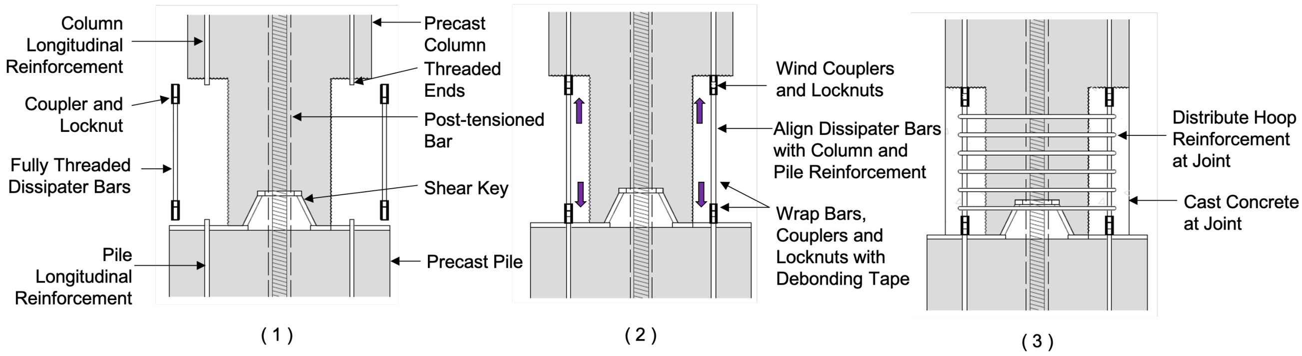


Figure 3: Installation methodology of internal dissipaters.

3.1 Material characterisation

Tensile tests were carried out to characterise the mechanical properties of the threaded Grade 300 M17 bars in tension as well as the failure mechanism between the threaded bar and coupler. Additional tensile tests were done on Grade 500E 16mm diameter deformed bars (YD16), which are used for the column and pile longitudinal reinforcement. The results of the tensile tests are summarised in Table 1. The failure strain was not measured in the tensile tests, as this would have damaged the extensometer.

Table 1: Summary of average tensile strength properties.

Bar	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Gr. 500E YD16	200.5	536	682
Gr. 300 M17	148	307	563

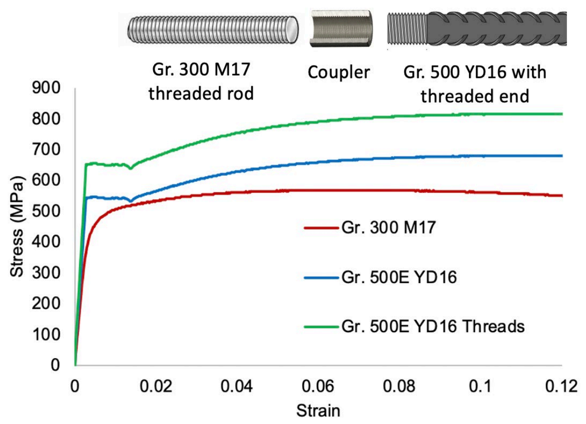


Figure 4: Stress-strain curve

Since the yield stress of the M17 bars is not clearly represented on the graph in Figure 4, as it shows material yielding gradually, it is estimated using the 0.2% offset method. The modulus of elasticity is taken as the slope of the elastic-range on the stress-strain curve. The tensile strength of the threaded ends of the YD16 bars was not tested; however, the stress-strain relationship is predicted in Figure 4, which shows an increase in tensile strength. In application to a DCR connection, the Grade 300 M17 bars are expected to yield before the adjacent grade 500E YD16 bars.

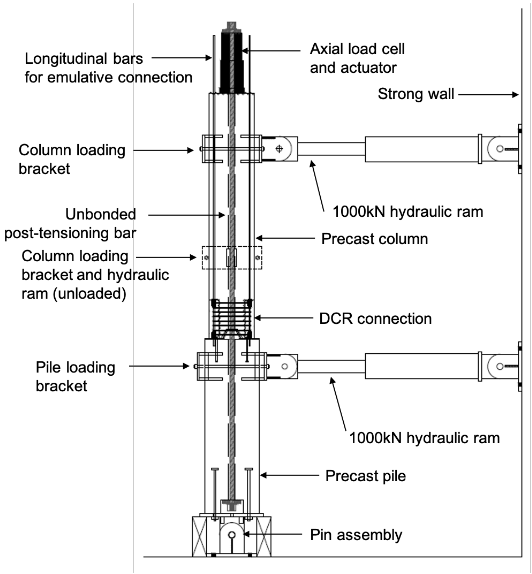
4 PROPOSED TESTING ARRANGEMENT

The proposed experimental campaign is being conducted as a means of obtaining experimental evidence to validate the theoretical predictions used to design a DCR pier founded on a monopile, and to validate numerical modelling for future parametric analysis.

The test setup will consist of two hydraulic rams that load the pier transversely at the column and pile. The position of the ram and magnitude of loading at the column was chosen to simulate transverse inertial loading of the specimen from the superstructure. The position of the ram and magnitude of loading at the pile was chosen to simulate the soil-pile interaction. A third ram will be attached at the mid-height of the column to prevent out-of-plane movement; however, this ram will not be loaded. Alternative solutions were investigated to model the soil-pile interaction, which included testing the pile in a soil box. However, using a hydraulic ram to represent the soil spring at the pile head was the most economical and feasible solution.

Lateral loading of the bridge pier will be cyclic, displacement controlled and quasi-static. Gravity loads on the column will be simulated using the unbonded post-tensioning, which run through a duct at the centre of the column and fixed mechanically at the bottom of the pile and top of the column. The bar will be stressed to the force level corresponding to the scaled gravity load as well as the load required for self-centring for the DCR configuration. Refer to Figure 5 for an illustration of the test setup.

The loading protocol used for testing is derived from ACI T1.1-01 (ACI Innovation Task Group 1 2001) in which three fully reversed cycles are applied at each drift ratio to the top of the column. The initial drift ratio is within the essential linear elastic response range for the module, and the subsequent drift ratios are 1.25 to 1.5 times the previous drift ratio. The loading protocol at the pile will be scaled to reflect the approximate passive soil reaction at the pile. The lateral drifts and corresponding displacements are plotted in Figure 6. As the column rocking is initiated, the ratio between the column and pile displacement increases.



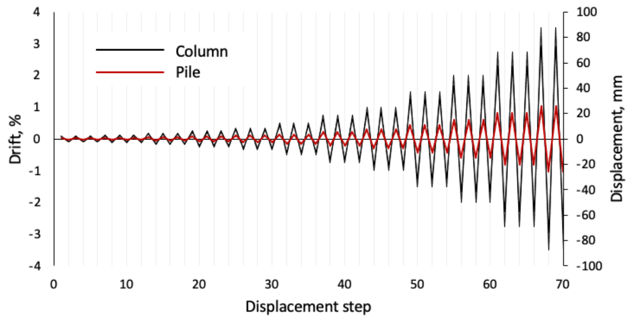


Figure 5: Test set up.

Figure 6: Loading protocol displacement history.

The precast column specimen will be constructed so that it can be utilised in two configurations. One end of the column will be detailed with a DCR connection. The other end of the column will be fabricated with the longitudinal bars protruding from the joint, as shown in Figure 5. To emulate a monolithic connection, the column will be inverted, and the protruded bars will be grouted into cast-in drossbach tubes in the pile.

5 NUMERICAL PREDICTION

5.1 Numerical model

A numerical model was developed to simulate the response of the DCR bridge pier in this study. The modelling of the DCR pier is based on the use of a multi-spring macro model (Fig. 7), which is the adopted modelling scheme as recommended by Marriott (2009) as it has the greatest potential in terms of accuracy versus computational effort. Compression-only non-linear link elements in SAP2000® were used to define the rocking interface at the base of the column. Spring elements were used to define the self-centring post-tensioned bar and dissipative steel bars. Since the column and pile are designed to remain elastic in a DCR pier, they are modelled as elastic frame elements. Linear elastic soil springs were defined along the length of the pile. Soil spring stiffness was defined assuming non-liquefiable medium-dense sand. It is also assumed that soil springs remain elastic under the design earthquake load.

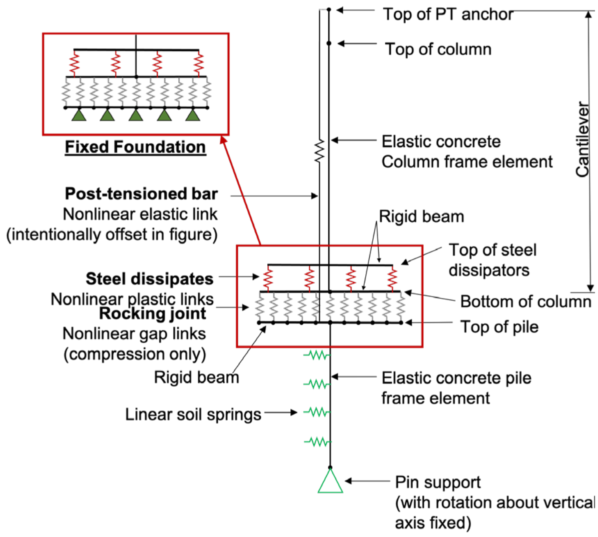


Figure 7: Multi-spring model adopted for cantilever bridge pier with DCR joint at the column-pile joint. The figure is not drawn to scale.

5.2 Numerical analysis

The response of a DCR bridge pier that is supported on a monopile and fixed foundation when incited by cyclic loading are plotted in Figure 8. The drift of the pile foundation is based on the relative displacement between the top of the column and pile. A symmetric force-displacement response is observed and resembles a flag-shape response that pinches at the origin indicating self-centring, as expected in a DCR system. The hysteretic response of the pier founded on a monopile does not pinch at the origin as much as the fixed foundation. This indicates that the DCR column supported on a pile foundation has a smaller self-centring capacity, especially at low drifts. It is evident that the additional rotations in the monopile and increase in unbonded post-tensioning length delay the onset of the rocking mechanism in the DCR column, which results in a delayed engagement of the post-tensioning. Additionally, the flexibility of the monopile reduces the DCR pier's stiffness and results in a reduced base shear and moment. The strains induced in the dissipaters are slightly reduced in the pier supported on a monopile.

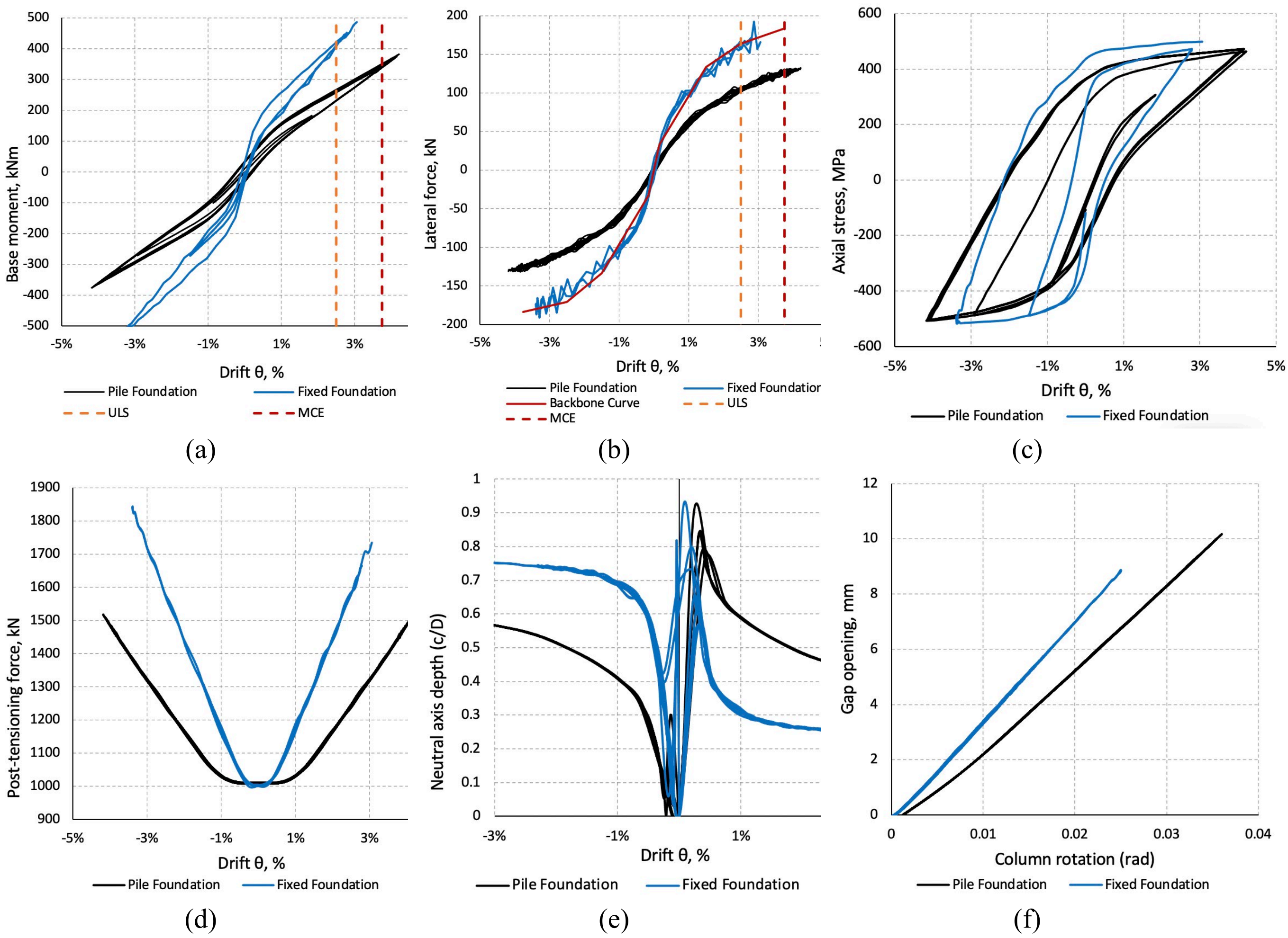


Figure 8: (a) Base moment, (b) lateral load, (c) axial stress in dissipater, (d) post-tensioning, (e) column-joint neutral axis displacement response and (f) gap opening response of DCR pier with fixed and pile foundation.

6 CONCLUSIONS

In this research, the use of a dissipative controlled rocking connection at the potential plastic hinge zone of a bridge column founded on a monopile is investigated. In the proposed connection, a combination of unbonded post-tensioning and internal dissipaters are used to provide self-centring and energy dissipation for the bridge substructure during an earthquake, respectively. A description of the experimental work that will be undertaken at the University of Canterbury on a one-third scale bridge pier is presented in this paper. In addition, the results of a numerical analysis are described which compares the predicted response of the DCR bridge pier founded on a monopile with one founded on a fixed base.

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